



A Review of the Distribution of Antibiotics in Water in Different Regions of China and Current Antibiotic Degradation Pathways

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Antibiotic pollution is becoming an increasingly serious threat in different regions of China. The distribution of antibiotics in water sources varies significantly in time and space, corresponding to the amount of antibiotics used locally. The main source of this contamination in the aquatic environment is wastewater from antibiotic manufacturers, large scale animal farming, and hospitals. In response to the excessive antibiotic contamination in the water environment globally, environmentally friendly alternatives to antibiotics are being developed to reduce their use. Furthermore, researchers have developed various antibiotic treatment techniques for the degradation of antibiotics, such as physical adsorption, chemical oxidation, photodegradation, and biodegradation. Among them, biodegradation is receiving increasing attention because of its low cost, ease of operation, and lack of secondary pollution. Antibiotic degradation by enzymes could become the key strategy of management of antibiotics pollution in the environment in future. This review summarizes research on the distribution of antibiotics in China's aquatic environments and different techniques for the degradation of antibiotics. Special attention is paid to their degradation by various enzymes. The adverse effects of the pollutants and need for more effective monitoring and mitigating pollution are also highlighted.

Keywords: antibiotic contamination, antibiotic resistance, enzyme degradation, water environment, ecosystems

INTRODUCTION

Since Fleming discovered penicillin in 1929, hundreds of other antibiotics have been synthesized, which are being increasingly used to treat infections in humans and animals. Inexpensive and effective antibiotics have become the preferred antibacterial drugs used by pharmaceutical and farming industries to inhibit the growth of bacteria and eliminate pathogens. In the aquaculture industry, antibiotics are used extensively as drugs to prevent bacterial infections and parasitic diseases (Bitchava and Nengas, 2010). Only a small portion of the antibiotics in aquatic products are actually absorbed, with most being discharged into the environment, resulting in antibiotic residues in aquaculture areas in discharged wastewaters and accumulated in the surrounding sediments through adsorption (Kumar et al., 2005; Conkle et al., 2010; Rico et al., 2013). In livestock farming, antibiotics are important for the prevention of infectious diseases and their treatment as well as for promoting the growth of livestock (Yin et al., 2016). Antibiotics applied to livestock and poultry are

not fully absorbed, with most being excreted into the environment through animal feces or urine (Briones et al., 2016). Residual antibiotics enter rivers and lakes through wastewater and accumulate in soil, where they are taken up by plants and animals (as illustrated in **Figure 1**).

As the world's most populous country and the largest consumer of antibiotics, China's antibiotic stewardship is facing significant challenges (Shao et al., 2020). Some of the antibiotics detected have been banned in clinical practice and may seriously impair human immunity (Zhou et al., 2021). In addition, exposure to veterinary antibiotics is associated with childhood obesity (Scott et al., 2016; Park et al., 2020) and liver injury (Mosedale et al., 2014), and the resulting genetic contamination of resistance poses serious threats to human health. China is vast territory with an equally diverse industrial layout. In addition, the levels of economic development vary greatly across the country, and thus the range of antibiotic concentrations in the environment is also broad across different regions. Here, first, we review the distribution of antibiotics in aquatic environments in China and the types of antibiotics, and report the distribution characteristics of antibiotics in China. Secondly, we analyze the potential impacts of antibiotics on the ecological environment in China. Lastly, we review progress in technologies for the degradation and removal of antibiotics in China and abroad, in addition to exploring the underlying principles, as well as their merits and shortcomings. This review provides a basis for risk estimation of antibiotics in ecological systems, an overview of the distribution of antibiotics in the aquatic environment in China, and the current approaches and methods used to eliminate antibiotics from ecological systems.

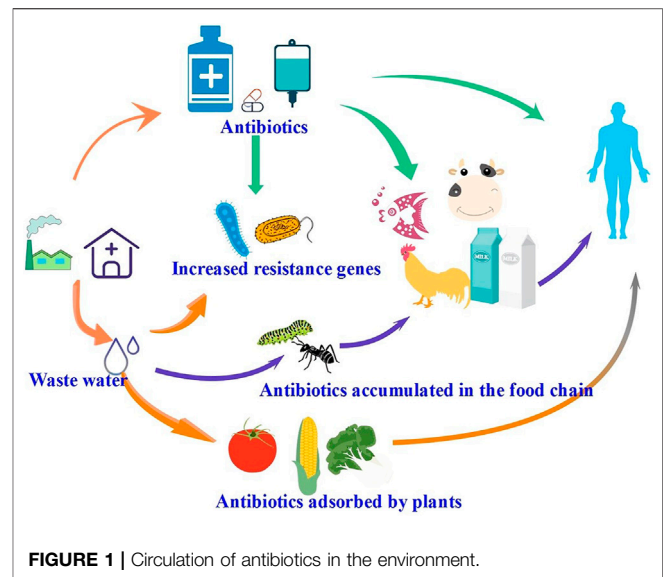
STATUS OF ANTIBIOTIC CONTAMINATION IN AQUATIC ENVIRONMENTS IN CHINA

Types of Antibiotics in Aquatic Environments in China

The major antibiotics in aquatic environments in China are divided according to their chemical structures and include macrolides, tetracyclines, fluoroquinolones, sulfonamides, and chloramphenicol (Liu et al., 2012). Their structural formulas are listed in **Table 1**.

Antibiotics in Surface Water

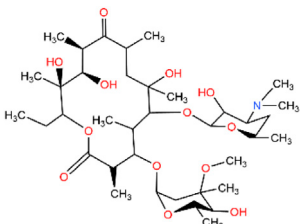
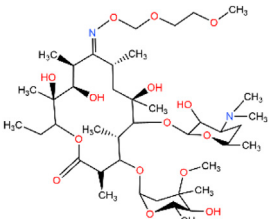
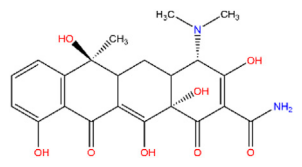
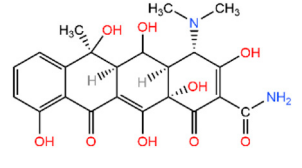
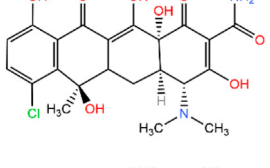
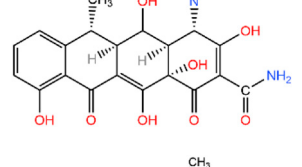
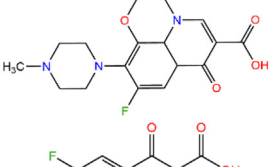
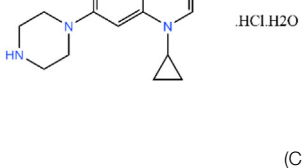
In different regions of China, the spatial and temporal distribution of antibiotics in water sources varies significantly, and this difference is closely related to the local industrial structure, the mode of antibiotic disposal in the pharmaceutical industry, and the mode of antibiotic use in the livestock industry. As shown in **Table 2** by the results of a statistical analysis of data from the last five years, the distribution of antibiotics have been found to vary in different areas, and their contamination level also varies from region to region (Zhang et al., 2019). The antibiotic pollution is mainly concentrated in the Yangtze River Basin, and the Bohai Bay and Pearl River Delta, and Xinjiang regions. In the western region, the medical safety standards are relatively poor, and



chloramphenicol, a highly effective antibiotic with relatively greater side effects, is a major problem. As a result of its continued use, the detection rate of chloramphenicol in the middle and upper reaches of the Yangtze River is significantly higher than that in the eastern region (Wang, 2020a). The pharmaceutical industry is concentrated in the economically developed eastern region, leading to the discharge of a large amount of antibiotic effluent and thus a high concentration of antibiotic pollution in this region (Bao et al., 2021). In Xinjiang, coastal areas, and other regions, the development of the livestock and aquaculture industries, which use antibiotics, has resulted in significantly higher levels of sulfonamides and tetracycline antibiotics in the environment. (**Table 3**). Quinolone antibiotics are widely used as broad-spectrum anti-infective drugs in medical treatment, and their presence has been detected in most local drinking water sources (**Table 4**). Generally, Chinese rivers and lakes have high concentrations of antibiotics. Sulfonamide and quinolone are the main pollutants in the surface waters of Chinese lakes (Liu et al., 2018).

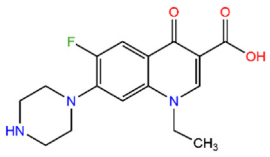
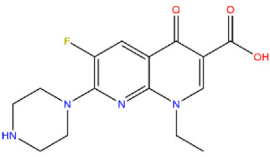
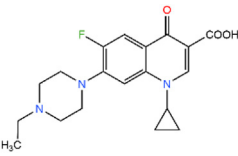
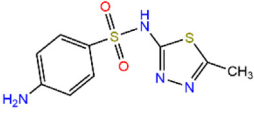
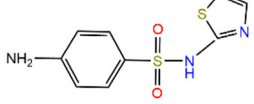
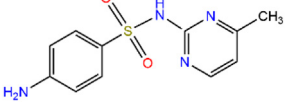
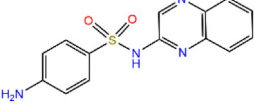
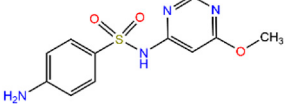
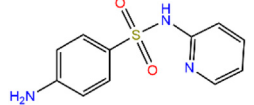
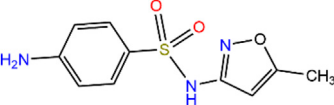
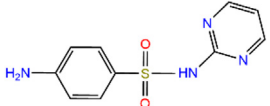
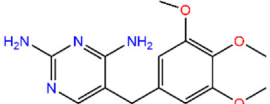
Antibiotics in the aquatic environment may be influenced by photolysis, temperature, pH, dilution factors, bacterial populations, and hydraulic residence time, leading to inconsistencies in their concentrations (Kummerer, 2009; Kümmerer, 2009; Zhang et al., 2014; Tang et al., 2015). Based on the results of previous research (Yoshizaki and Tomida, 2000; Loftin et al., 2008; Ben et al., 2013), the concentrations and compositions of the main types of antibiotics in the abundant water period and dry water periods are shown in **Figure 2**, which show that the concentrations of antibiotics in aquatic environments vary seasonally, with detectable frequencies and average concentrations being higher in winter (dry water period) than in summer (dry water period). Industrial structure, medical level, and climate of different regions have an effect on the distribution of antibiotics in local water bodies, especially pharmaceutical and farming industries have a marked effect on antibiotic discharge. Therefore, strengthening guidance and

TABLE 1 | Major classes of antibiotics in aquatic environments in China.

Type	Name	Abbreviation	Structure	CAS No.
Macrolides	Roxithromycin	ROX		80214-83-1
	Erythromycin	ERM		114-07-8
Tetracyclines	Tetracycline	TC		60-54-8
	Oxytetracycline	OTC		79-57-2
	Chlorotetracycline	CTC		57-62-5
	Doxycycline	DOX		209-271-1
Fluoroquinolones	Ofloxacin	OFX		82419-36-1
	Ciprofloxacin	CIP		85721-33-1 HCl.H ₂ O

(Continued on following page)

TABLE 1 | (Continued) Major classes of antibiotics in aquatic environments in China.

Type	Name	Abbreviation	Structure	CAS No.
	Norfloxacin	NOR		70458-96-7
	Enoxacin	ENX		74011-58-8
	Enrofloxacin	EFX		93106-60-6
Sulfonamides	Sulfamethizole	SMT		144-82-1
	Sulfathiazole	STZ		72-14-0
	Sulfamerazine	SMR		127-79-7
	Sulfaquinoxaline	SQX		59-40-5
	Sulfamonomethoxine	SMM		651-06-9
	Sulfapyridine	SPD		144-83-2
Chloramphenicols	Sulfamethoxazole	SMX		723-46-6
	Sulfadiazine	SDZ		68-35-9
	Trimethoprim	TMP		738-70-5

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TABLE 1 | (Continued) Major classes of antibiotics in aquatic environments in China.

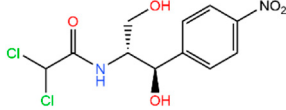
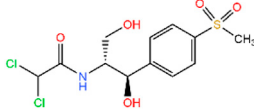
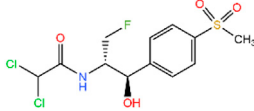
Type	Name	Abbreviation	Structure	CAS No.
	Chloramphenicol	CAP		56-75-7
	Thiamphenicol	TAP		15318-45-3
	Florfenicol	FF		73231-34-2

TABLE 2 | Distribution of antibiotics in different waters of China (From 2015 to 2020).

Waters	Regions	The amount of antibiotics detected (ng/L)					References
		Sulfonamides	Fluoroquinolones	Macrolides	Chloramphenicols	Tetracyclines	
Songhua river	Harbin	2.1~92.14	0.03~8.14	0.26~18.07	—	—	Wang et al. (2018c)
Lancang river	Lincang	1.51~37.43	0.03~1.45	0.18~4.46	—	ND~12.19	Liang (2019)
Yarlung zangbo river	Lasa	2.74~33.94	<2	0.61~33.77	—	0.70~14.07	Liang (2019)
Huangpu river	Shanghai	0~22.48	—	—	—	9.98~177.28	Fang et al. (2017)
Yangtze river (nanjing section)	Nanjing	32.42	27.25	778.49	6.46	14.55	Feng et al. (2019)
Moon lake	Ningbo	13.68~523.78	ND~267.0	5.88~552.53	—	—	Wang et al.,(2018d)
Taihu lake basin (yili-taohang section)	Changzhou-wuxi	ND~0.58	ND~0.21	0.04~0.94	—	ND~17.85	Sun et al.,(2018)
Taihu gonghu bay	Wuxi	ND~478	14~474	14~23	—	ND~4,720	Wu et al. (2016)
Tiaoxi (taihu lake basin)	Huzhou	≤326.6	≤36.5	—	—	ND	Xu et al. (2020)
Poyang lake	Nanchang	1.3~117	—	3.6~14.8	5~16.5	ND~106.5	Ding (2018)
Chaohu	Hefei	ND~189.9	ND~148.7	ND~18.48	—	ND~14	Tang et al. (2014)
South lake	Wuhan	3.52~20.48	70.70~155.52	—	—	21.41~43.43	Xiao et al. (2019)
Shahu	Wuhan	ND~0.81	37.85~75.09	—	—	20.06~29.03	Xiao et al. (2019)
East lake	Wuhan	ND~4.17	49.49~83.31	—	—	15.42~24.64	Xiao et al. (2019)
Datong lake	Yiyang	11.56~181.25	ND~83.53	—	—	ND~18.08	Liu and Lu (2018)
Yangtze river basin (three gorges Section)	Chongqing	ND~247	ND~16.4	19.1~223.7	11.9~615.8	—	Feng et al. (2017)
Nanming river	Guiyang	13.68~523.78	1.72~424.37	5.88~552.53	1.95~235.6	0.36~243.25	Wang et al. (2018e)
Weihe river (Xi'an section)	Xi'an	21.37~60	4.7~64.28	—	—	4.64~129.91	Zhu et al. (2018)
Pearl river	Guangzhou	687.90	814.1	1112.2	—	643.2	Liu et al., 2017)
Star lake	Zhaoqing	9.27~190.71	2.27~9.46	ND~0.8	—	ND	Xie et al. (2019)
Caohai karst plateau wetland	Weining	50.5	43.2	22.6	15.9	ND	Wang et al. (2020a)
Huaihe (shihe district)	Xinyang	—	—	13.1~355.6	—	ND~275.1	Wang and Wang (2020)
Xiaoqinghe (jinan section)	Jinan	DN~196.5	11.0~383.9	13.16~309.09	—	ND~8.91	Yan (2018)
Ebinur lake	Bortala Mongolian autonomous prefecture	22.50~103.72	21.61~83.78	0.56~306.75	—	ND~15.94	Wang (2020b)
Bosten lake	Bayingoleng Mongolian autonomous prefecture	ND~36.81	ND~99.32	—	—	ND~43.55	Yang (2018)
Ebinur lake	Alashankou	ND~61.01	293.78~5144.95	—	—	ND~12.01	Qianqian (2016)

TABLE 3 | Antibiotic concentrations in surface water in aquaculture areas (From 2015 to 2020).

Waters	Regions	The amount of antibiotics detected (ng/L)					References
		Sulfonamides	Fluoroquinolones	Macrolides	Chloramphenicols	Tetracyclines	
River estuary area	Dongying	0.01~11.4	0~63.3	ND~16.5	0.09~0.51	ND	Lian (2016)
Gate of yang county	Yancheng	1~2.35	3.77~9.76	0.15~2.05	2.91~3.44	ND	Han et al. (2020)
Aquaculture ecosystem in haiyang regions	Haiyang	1.41~6.72	2.14~180.14	0.32~45.66	—	ND~2.09	Chen et al. (2015)
Marine aquaculture farms	Yangjiang	1181.64	932.05	1158	—	>1536	Zhang et al. (2018b)
Maowei sea breeding pond	Guangxi province	2.6	3	71.7	8.9	—	Zheng et al. (2017)
Freshwater aquaculture area	Zhejiang province	73.6~171.1	94.1~113.2	ND	—	—	Xu et al. (2019)
Aquaculture pond	Huzhou	ND~12,623	ND~332.3	—	—	ND~5.6	Wang et al. (2019)
Tilapia farming pond	Guangxi province	44.3	14.7~22.7	—	ND	32.7~3242	Yu et al.(2020)
Procambarus clarkii breeding area	Jiangsu province	ND~198.827	ND~38.82	ND~38.471	—	ND~114.296	Zhang et al. (2019)
Aquaculture area	Shanghai	ND~83.6	ND~3.27	—	—	ND~27.53	Zhong et al. (2018)
Beijiang river and its surrounding aquafarms	Guangdong province	1016.4	480	375.8	210.5	277.5	Wang et al. (2017b)
Aquaculture ponds	Honghu	32~1096.8	18~334.3	—	—	204.1~3028.3	Yuan et al. (2019)
Hangzhou bay	Zhejiang province	16.6~44.13	41.11~115.28	—	8.41~28.57	25.98~50.2	Hao et al. (2017)
Nansha aquaculture area	Guangzhou	0.81	ND	78.01	—	—	Chen et al. (2018)
Panyu aquaculture area	Guangzhou	113~247	0~100	80~1400	—	—	Lian (2016)

TABLE 4 | Antibiotic concentrations in drinking water sources in some cities (From 2015 to 2020).

Waters	Regions	The amount of antibiotics detected (ng/L)					References
		Sulfonamides	Fluoroquinolones	Macrolides	Chloramphenicols	Tetracyclines	
Huizhou water supply plant	Huizhou	47.73	ND	11.65	—	ND	Zheng (2017)
Beijing groundwater	Beijing	ND~341.2	ND~49.5	—	—	ND~3.2	Chen et al. (2017)
Drinking water in qingyuan	Qingyuan	ND~62.63	ND~295.09	ND~9.94	ND	ND	Dai (2019)
Biliuhe reservoir	Dalian	ND~15	ND~130	ND	ND~17	—	Dong et al. (2020)
Lianhua reservoir	Xiamen	ND~11.96	ND~353.42	ND~305.19	—	ND~254.67	Liao et al. (2020)
Drinking water sources	Dongguan	24.63~38.7	11.11~82.24	27.25~206.65	—	20.08~43.02	Xie et al. (2020)
Reservoir	Chongqing	ND~40.2	—	ND~60.1	1.1~35.4	—	Feng et al. (2020)
Water plant	Suzhou	4.65	2.29	1.51	—	1.45	Di et al. (2019)
Drinking water sources	Nanjing	ND~29.58	ND~40.18	0.53~35.25	—	ND~35.61	Liu et al. (2020a)
Drinking water sources	Jiaxing	0.69~13.21	89.5~230.8	ND~56.9	121~259	—	Guo et al. (2016)
Taipu river and jinze reservoir	Shanghai	10.5~385.8	10.2~189.4	ND~56.8	—	8.1~135.5	Li et al. (2020a)
Fengshuba reservoir	Guangdong province	4.29~39.45	ND~302.76	ND~1.57	—	3.44~345	Chen et al. (2020b)

regulations of the above industries is the main approach to reduce antibiotic discharge.

Antibiotics in Sediment

Antibiotics have been detected not only in water bodies such as lakes but also in sediments, which can contain significant amounts. The level of exposure of sediments to antibiotics is usually higher than that of water because the sediment particles, which have a strong ability to adsorb antibiotics (Lee and Carlson, 2006; Kim and Carlson, 2007; ; Yang et al., 2010). Antibiotic concentrations in surface water are more susceptible to external environmental influences than those in sediment, including dilution (Cheng et al., 2014; Ding et al., 2017), adsorption of particles (Wang et al., 2017a; Yang et al., 2020), and photodegradation (Chen et al., 2016), all of which can affect

the variation of the antibiotic concentrations in water. Compared to in the water column, antibiotic levels in sediments are relatively stable because their ability to strongly adsorb antibiotics leads to antibiotic accumulation in the sediments (Mangalgiri and Blaney, 2017). Different water environments lead to different adsorption properties of the sediments, resulting in a both spatially and geographically heterogeneous distribution of antibiotics in sediments, as shown in **Table 5**. Furthermore, this distribution may also be influenced by the external environment. For example, external currents may flush antibiotics-bearing sediments and thus release adsorbed antibiotics into the aquatic environment, causing secondary pollution (Radke et al., 2009). Sediments can affect the level of antibiotics in water bodies. The components of sediments are highly complex, and there are several differences in the composition of sediments in different water body

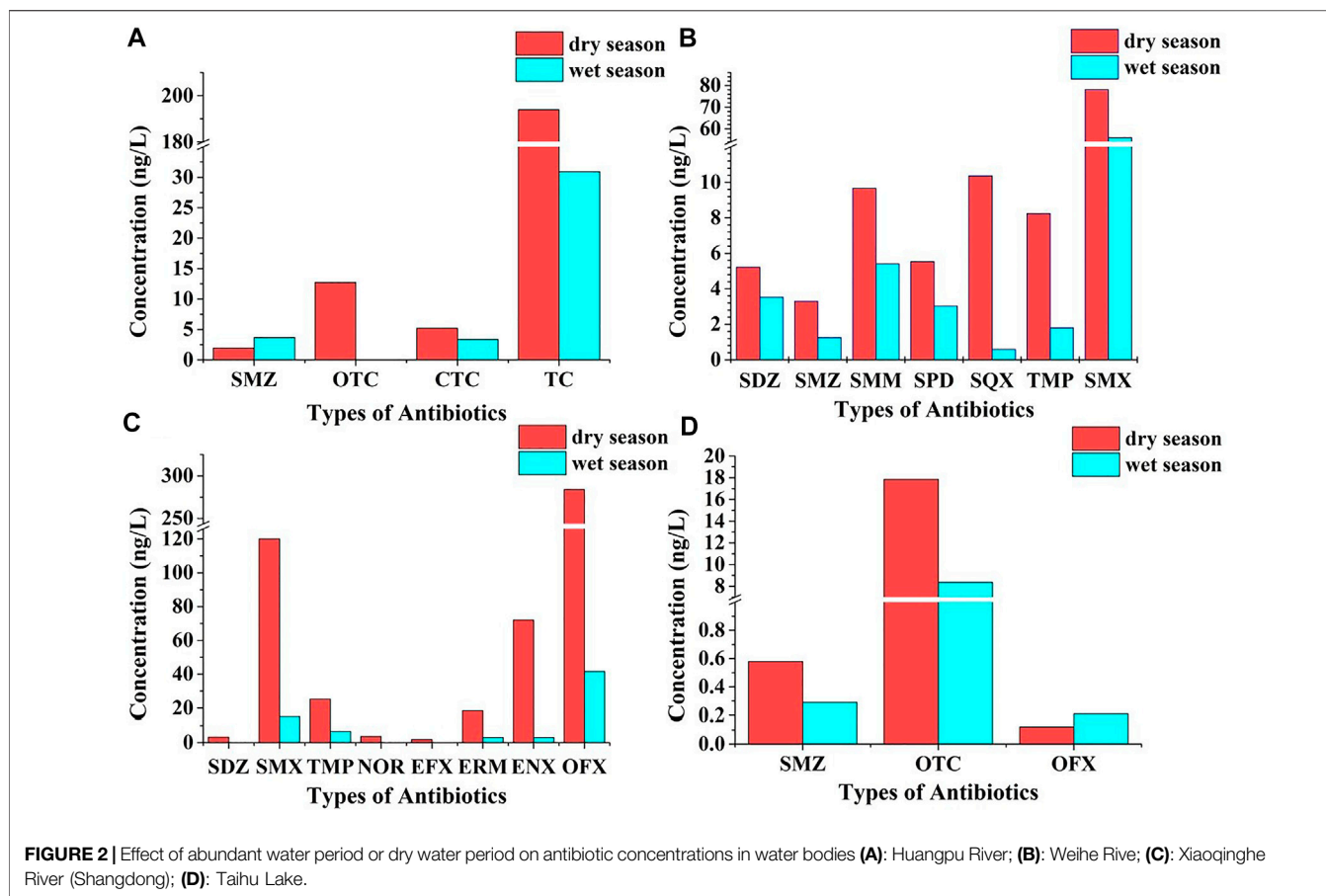
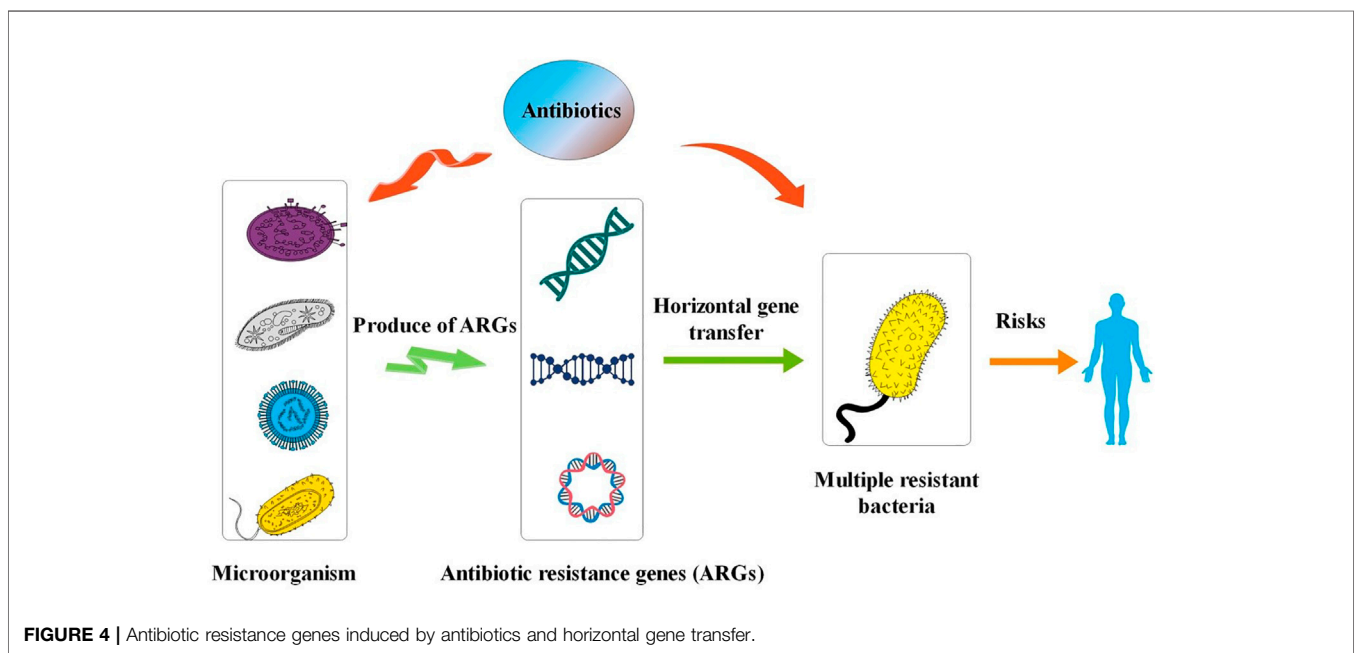
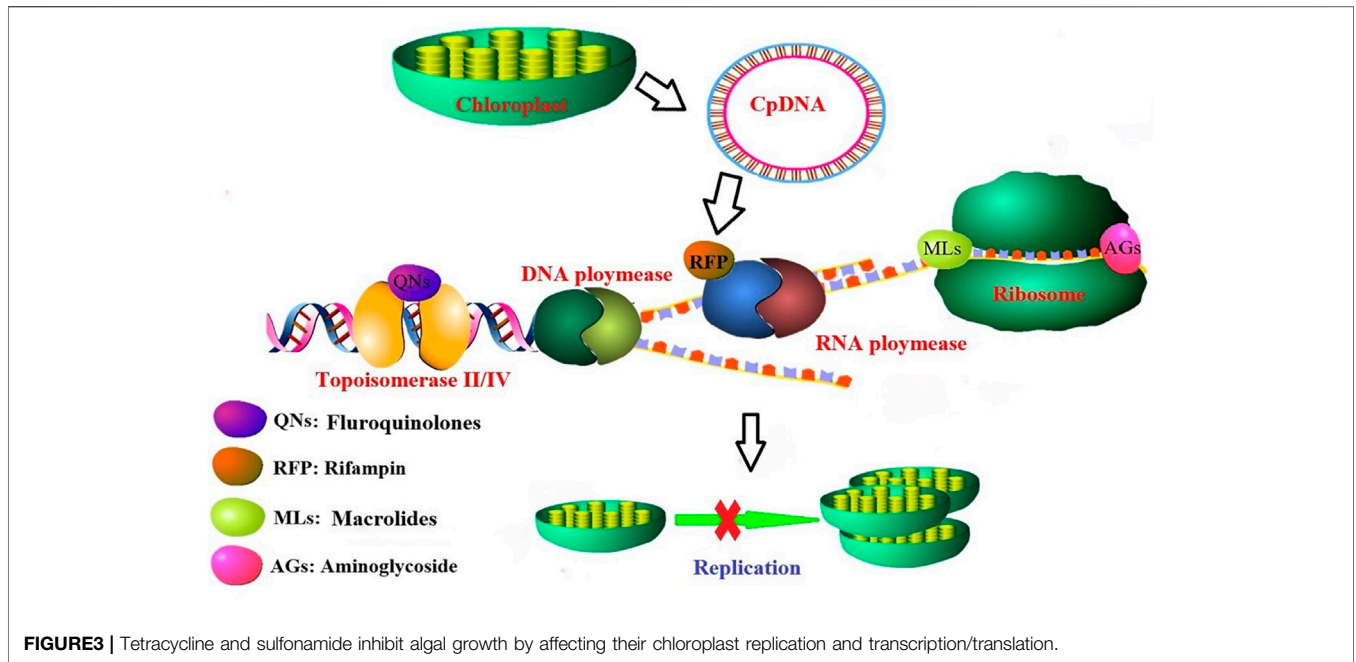


TABLE 5 | Antibiotics concentrations in sediment (From 2015 to 2020).

Waters	Regions	The amount of antibiotics detected (ng/L)					References
		Sulfonamides	Fluoroquinolones	Macrolides	Chloramphenicols	Tetracyclines	
Yangtze river/Jialing river (chongqing selection)	Chongqing	2.79~23.19	22.24~33.15	7.6~14.07	—	7.02~9.76	Wang et al. (2020b)
Danjiangkou Reservoir	Danjiangkou	1.0~15	1.6~16	—	—	2.7~22	Hu et al. (2019)
Pearl river estuary	Zhuhai	ND~192	ND~157	ND~114	—	ND~206	Li et al. (2018)
Taihu lake		0.086~9.169	0.28~50.1	0.97~67.38	—	0.102~28.66	Xu et al. (2018)
Minjiang estuary	Fuzhou	ND~1.33	0.03~15.60	0.02~44.31	—	ND	Liu et al. (2020b)
Intertidal mudflat culture areas	Da'lian	0.4312~22.457	4.682~78.368	—	0.953~1.436	—	Xuan et al. (2020)
Aquaculture area		ND~71.49	ND	ND~13.19	—	—	Qian et al. (2019)
Yangtze estuary (wusongkou)	Shanghai	2.63	48.98	8.54	0.93	19.71	Guo et al. (2020)
Yangtze estuary	Xupu	ND	16.28	2.74	ND	0.96	Guo et al. (2018)
Nanfei river	Hefei	ND~2.7	ND~311	ND~15.8	—	—	Lyu et al. (2019)
Songhua river	Jilin	ND~26.9	ND~7.1	3.0~28.3	ND~15.4	5.9~32.9	He et al. (2018)
Liao river	Jilin	ND~5.2	ND~640	ND~512	—	ND~78.8	Dong et al. (2016)
Mangrove nature reserves	Hainan	57	48.8	26.4	5.6	24.5	Liu et al. (2020c)
Mangrove nature reserves	Hongkong	39.1	28	126.6	7.7	95.6	Liu et al. (2020c)
Fengshuba reservoir	Heyuan	2.91~46.22	15.81~172.9	18.98~180.6	—	ND	Chen et al. (2020b)
Chaobai river	Beijing	7.7	432.9	12.13	—	225.8	Zhang et al. (2020b)
East China sea bay	Zhengjiang	0~25.3	0.4~45.1	0.6~60.3	—	0~108	Li et al. (2020b)
Xiangjiang river	Hunan	ND~0.98	3.77~487	0.33~9.44	ND~9.03	1.56~1115	Chen et al. (2019)



environments. The enrichment of antibiotics in sediments and how antibiotics in sediments are released into the water body still need systematic and in-depth research.

EFFECT OF ANTIBIOTICS ON PEOPLE AND ECOSYSTEMS

Antibiotic Hazards to Human Health

Antibiotics have been found in fish from some farming areas and in some cooked foods and crops, and the antibiotics can be

enriched in humans after consumption. Antibiotics have a strong inhibitory effect on the entire intestinal bacterial community (He et al., 2014). Antibiotics have a strong inhibitory effect on the entire bacterial community of intestinal microorganisms. The transfer of resistance genes between intestinal endophytes and pathogenic bacteria such as *Escherichia coli*, *Klebsiella*, and *Enterococcus faecalis* leads to an imbalance in intestinal microorganisms, and this in turn causes a variety of bacterial diseases (McInnes et al., 2020) and even intestinal cancer (Sobhani et al., 2019) and experiments have shown that even a small amount of antibiotics rapidly

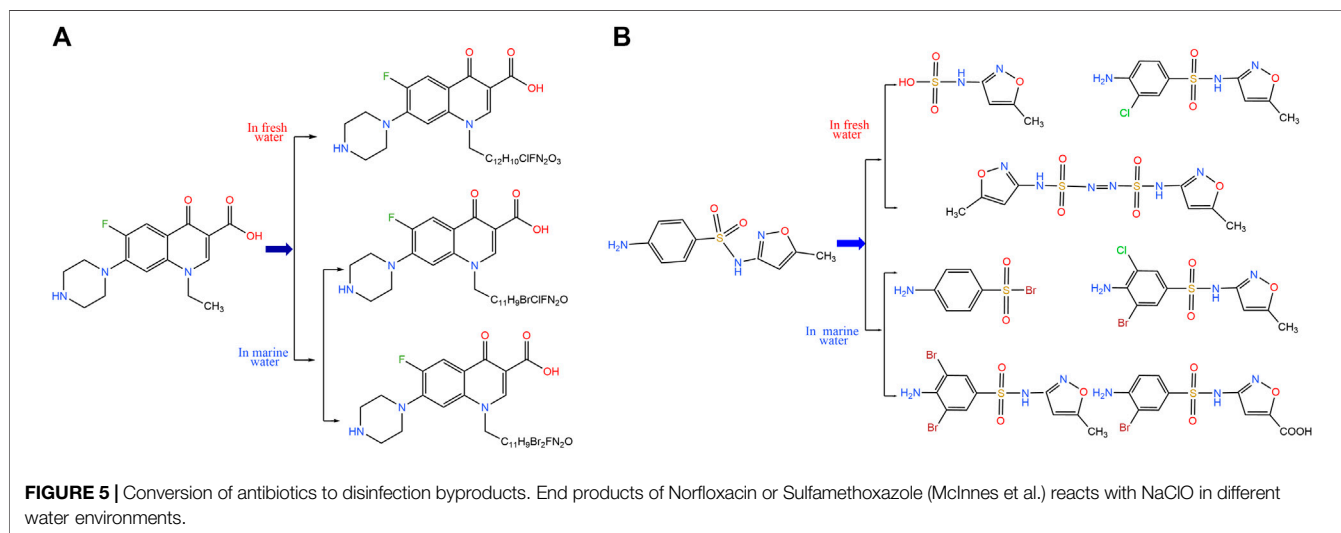


TABLE 6 | Characteristics of different methods of degrading antibiotics.

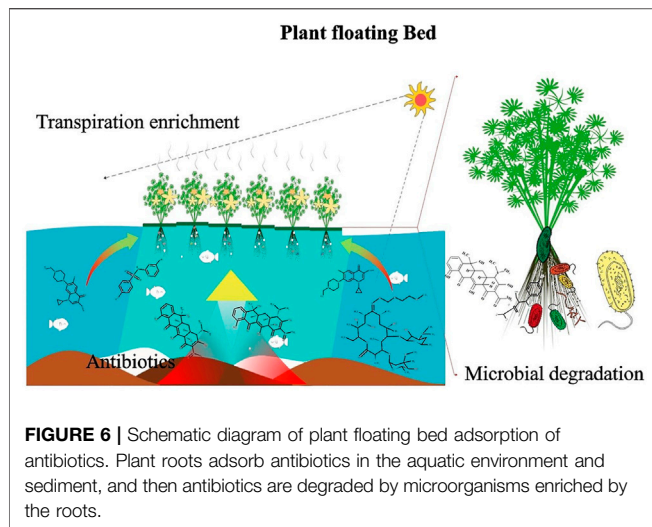
Methods of degrading antibiotics	Stages of application	Advantages	Disadvantages	References
Physical adsorption	Scaled up applications in industry	Low cost, simple design, and high flexibility	Low efficiency and causes secondary pollution	Dutta and Mala (2020)
Membrane filtration	Applications in drinking water production	Removal of many contaminants	High cost	Yin et al. (2021)
Chemical oxidative degradation	Scaled up applications in industry	Easy to operate, requires short time, and efficient	Environmentally unfriendly and low recycling rate	(Advanced oxidation technology engineering.)
Photolysis	In the laboratory research stage	Eco-friendly	High cost	Bo (2017)
Plant adsorption	Scaled up applications in industry	Economical, with high efficiency	Selective and diffusion of resistance genes	Liu et al. (2019)
Activated sludge and microbial strains	Scaled up applications in industry	Efficient and easy to operate	Susceptible to microbial resistance gene production	Liu et al. (2016)
Enzymatic degradation	In the laboratory research stage	Eco-friendly, efficient, and requires short time	Highly influenced by environment	Bilal et al. (2019)

changes the diversity of the intestinal flora in a short period of time (Dethlefsen et al., 2007; Fouhy et al., 2012), which may lead to a variety of diseases, especially in newborns. Antibiotic use during pregnancy or in newborns may adversely affect the neonatal gut microbiome and adversely affect the development of the infant's immune system, leading to childhood atopy, asthma, allergies, and obesity. It increases the probability of epilepsy in children (Kenyon et al., 2008; Neu and Walker, 2011; Madan et al., 2012; Mette et al., 2012; Dik et al., 2016; Koebnick et al., 2019; Milliken et al., 2019; Pronovost and Hsiao, 2019; Tadeusz et al., 2019; Zimmermann and Curtis, 2020; Zhang et al., 2021). Excessive intake of antibiotics can cause damage to the nervous system, kidneys, and other organs (Ramirez et al., 2007). At the same time, germs are prone to develop drug resistance and become super germs that are difficult to cure (Goldman, 2004; Xu et al., 2010). The dose of antibiotics used to treat a disease is controllable, but the

enrichment of antibiotics from food into the body is not measurable and assessable. As food is consumed every day, determining the content of antibiotics contained in food is difficult. Therefore, the regulation of antibiotic content in food in the market is important.

Antibiotic Accumulation in the Ecological Chain

Algae are the basis of the food chain, and even a slight decrease in algal populations may affect the balance of the aquatic system (Lanzky and Halling-Sørensen, 1998). Researchers performed relevant cytotoxicity experiments to verify that the presence of antibiotics affects the genetic and normal growth of the genome (Yamaguchi et al., 2003; Yamaguchi and Subramanian, 2003). As shown in **Figure 3**, tetracycline and sulfonamide antibiotics have been found to inhibit algal growth by affecting their chloroplast



replication, transcription/translation, and metabolic pathways (Brain et al., 2004; Brain et al., 2008; Baran et al., 2011). Fish appear to be less sensitive to antibiotics than algae (Li et al., 2012a). Feeding habits can affect the accumulation of antibiotics in fish, and some studies have shown that carnivorous fish have higher levels of antibiotic enrichment than other fish because they are the top consumers in the food chain in the aquatic environment (He et al., 2014). Zhao et al. showed that the accumulation of antibiotics in different tissues of animals is different, and the accumulated antibiotic levels in different tissues of fish are also different. For example, the accumulation levels of antibiotics in fish bile, plasma, and liver are relatively higher than those in other organs. (Zhao et al., 2016a). Invertebrates and fish that are chronically exposed to antibiotics are enriched in antibiotics, and people who consume these aquatic organisms face a high health risk (Metsälä et al., 2015; Wang et al., 2015; Möhle et al., 2016; Siswanto et al., 2016; Winek et al., 2016). The toxicity of antibiotics in water is influenced by their concentration, duration of exposure, aquatic species, and the coexistence of other antibiotics and/or other contaminants (Grenni et al., 2017). Plants can take up multiple antibiotics from soil and water, and while the toxicities of these multiple antibiotics are not superimposed on a single toxicity, they can induce combined toxicity (Brain et al., 2004). Antibiotics are passed up the food chain, resulting in human exposure to antibiotics *via* the consumption of food containing antibiotics; eventually, the accumulated antibiotics will have negative effects on the human body.

Increase of Potential Novel Antibiotic Resistant Gene Induction by Antibiotics

Genes are mutated and inherited in nature, and antibiotic resistance genes (ARGs) are present in the natural environment. Thus, antibiotics released into the environment exert selective pressure on the microbial community, thereby inducing drug-resistant bacteria and causing widespread bacterial resistance (Wei et al., 2019). Residual antibiotics and ARGs that

enter the environment can be taken up by plants and enter the food chain through the migration distribution of the soil-water plant system (Forsberg et al., 2012), where they migrate and accumulate, and eventually enter the human body. There are two main sources of ARGs in the environment (Zhang et al., 2019a): ARGs are present in the environment itself—Antibiotics are mainly derived from secondary metabolites of microorganisms, plants, and animals, and these microorganisms are resistant to the antibiotics they produce (Russell and Yost, 2020); 2) Another source of ARGs is exogenous input (Zhang et al., 2018a). The metabolism rate of antibiotics in animals is very low, and about 25–75% of the antibiotics enter the environment through excreta without having been metabolized, thus inducing the production of resistance genes in the environment. As illustrated in **Figure 4**, ARGs can be transmitted between microorganisms and vertically between generations through horizontal gene transfer (HGT). As microorganisms evolve, new ARGs may also be produced (Ji et al., 2012; Shi et al., 2015). A wide variety of microorganisms in the environment may even lead to the creation of multidrug resistance genes or superbugs, while also increasing the potential for the induction of novel ARGs. The food chain can enhance the spread of resistance genes (Hu et al., 2016; Johnson et al., 2016). The transfer of ARGs acquired by humans from the environment or from food to gut microbes leads to an increase in gut microbial resistance (Huddleston, 2014). Studies have identified β -lactamase genes in the metabolic genome of human gut flora (Cao et al., 2021), suggesting that human gut microbes can acquire resistance genes from the environment, thereby leading to drug-resistant infections in human (Bengtsson-Palme, 2017).

Antibiotics and Disinfection Byproducts

In addition to their own toxicological effects and the genetic problem of resistance, antibiotics that remain in the aquatic environment have been found by researchers to be precursors of disinfection byproducts (DBPs) that can react with disinfectants such as chlorine and chlorine dioxide to produce halogenated carbon or nitrogen-containing disinfection byproducts (Wang and Helbling 2016; Zhang et al., 2017; Chuan et al., 2018) (**Figure 5**). DBPs are the result of the reaction between disinfectants and a special class of organics produced by the reaction of organic precursors in water. Since many antibiotics are nitrogen-containing organics, they contribute significantly to some of the more toxic N-DBPs. These disinfection byproducts, in turn, can be instrumental in inducing antibiotic resistance and resistance genes. DBPs have been shown to significantly increase bacterial resistance to antibiotics (Lü et al., 2015) and the mutagenesis rate of resistance genes (Li et al., 2016) as well as the concentration of resistant bacteria (Lv et al., 2015). The level of DBPs is often overlooked when testing for antibiotics in water, and we need to pay equal attention to the level of DBPs, which can also lead to the development of resistance genes in bacteria.

Antibiotics in Aquatic Organisms

Low concentrations of antibiotics are present in fish; however, they are mainly detected in laboratory studies. The

TABLE 7 | Antibiotic adsorption by plants reported in the literature.

Antibiotics	Plant	Removal (%)	References		
Sulfonamides	Sulfadiazine	<i>Thalia</i>	72 ± 6	Dan et al. (2013)	
	Sulfadiazine	<i>Arundo</i>	74 ± 6	Dan et al. (2013)	
	Sulfadiazine	<i>Waseyutaka</i>	98.7	Xian et al. (2010)	
	Sulfadiazine	<i>Acorus calamus</i>	26.42–64.93	Chen et al. (2020a)	
	Sulfamethoxazole	<i>Cyperus alternifolius</i>	76.77 ± 4.13	Kumar et al. (2005)	
	Sulfamethoxazole	<i>Dryan</i>	91.8	Xian et al. (2010)	
	Sulfamethoxazole	<i>T. angustifolia/P. australis</i>	60 ± 26	Hijosa-Valsero et al. (2011a)	
	Sulfamethoxazole	<i>Acorus/Typha</i>	29–52	Park et al. (2009)	
	Sulfamethoxazole	<i>Thalia Dealbata Fraser</i>	56.9 ± 7.36	Jun et al. (2016)	
	Sulfamethoxazole	<i>Iris tectorum Maxim</i>	69.2 ± 2.24	Jun et al. (2016)	
	Sulfamethoxazole	<i>T. angustifolia</i>	80 ± 42	Hijosa-Valsero et al. (2011b)	
	Sulfamethoxazole	<i>Acorus calamus</i>	37.81–84.05	Chen et al. (2020a)	
	Sulfamethazine	<i>Waseyutaka</i>	88.8	Xian et al. (2010)	
	Sulfamethazine	<i>Tachimasari</i>	89.4	Xian et al. (2010)	
	Sulfamethazine	<i>H. pennisetum</i>	91–95	Liu et al. (2013)	
	Sulfamethazine	<i>Thalia Dealbata Fraser</i>	100 ± 0.00	Jun et al. (2016)	
	Sulfamethazine	<i>Iris tectorum Maxim</i>	100 ± 0.00	Jun et al. (2016)	
	Sulfamethazine	<i>Acorus calamus</i>	18.98–65.06	Chen et al. (2020a)	
	Sulfadimethoxine	<i>T. angustifolia</i>	99 ± 2	Hijosa-Valsero et al. (2011b)	
	Sulfadimethoxine	<i>P. australis</i>	99 ± 2	Hijosa-Valsero et al. (2011b)	
	Trimethoprim	Trimethoprim	<i>Thalia</i>	31 ± 37	Dan et al. (2013)
		Trimethoprim	<i>Arundo</i>	38 ± 10	Dan et al. (2013)
		Trimethoprim	<i>Thalia Dealbata Fraser</i>	84.6 ± 2.26	Jun et al. (2016)
Trimethoprim		<i>Iris tectorum Maxim</i>	84.4 ± 2.28	Jun et al. (2016)	
Lincosamides		Roxithromycin	<i>Cyperus alternifolius</i>	85.35 ± 2.47	Kumar et al. (2005)
		Leucomycin	<i>Thalia Dealbata Fraser</i>	100 ± 0.00	Jun et al. (2016)
		Leucomycin	<i>Iris tectorum Maxim</i>	100 ± 0.00	Jun et al. (2016)
		Clarithromycin	<i>Thalia Dealbata Fraser</i>	74.2 ± 5.63	Jun et al. (2016)
		Clarithromycin	<i>Iris tectorum Maxim</i>	87.3 ± 0.86	Jun et al. (2016)
Tetracyclines		Erythromycin	<i>P. australis</i>	64 ± 30	Hijosa-Valsero et al. (2011b)
	Oxytetracycline HCl	<i>H. pennisetum</i>	68–73	Liu et al. (2013)	
	Oxytetracycline	<i>P. australis</i>	92.7–99.9	Huang et al. (2015)	
	Oxytetracycline	<i>H. annuus</i>	100	Gujarathi et al. (2005)	
	Oxytetracycline	<i>Typha orientalis</i>	72.43	Zhao et al. (2016b)	
	Chlorotetracycli	<i>P. australis</i>	69.0–99.7	Huang et al. (2015)	
	Chlorotetracycli	<i>Typha orientalis</i>	73.84	Zhao et al. (2016b)	
	Tetracycline	<i>P. australis</i>	88.4–98.3	Huang et al. (2015)	
	Tetracycline	<i>P. australis</i>	99.3 ± 0.4	Fernandes et al. (2015)	
	Tetracycline	<i>Typha orientalis</i>	70.85	Zhao et al. (2016b)	
	Tetracycline	<i>H. annuus</i>	100	Gujarathi et al. (2005)	
	Doxycycline	<i>T. angustifolia</i>	75 ± 40	Hijosa-Valsero et al. (2011b)	
	Fluroquinolones	Ciprofloxacin HCl	<i>H. pennisetum</i>	78–84	Liu et al. (2013)
Enrofloxacin		<i>P. australis</i>	98.7 ± 0.3	Fernandes et al. (2015)	
Difloxacin		<i>Phragmites australis</i>	>84	Jun et al. (2016)	
Other PPCPs	Naproxen	<i>Acorus/Typha</i>	52–92	Park et al. (2009)	
	Naproxen	<i>Phragmites australis</i>	80 ± 9	Matamoros and Bayona (2006)	
	Ibuprofen	<i>Phragmites australis</i>	62 ± 2	Matamoros and Bayona (2006)	
	Diclofenac	<i>Acorus/Typha</i>	73–96	Park et al. (2009)	
	Carbamazepine	<i>Acorus/Typha</i>	30–47	Park et al. (2009)	
	Methyl dihydrojasmonate	<i>Phragmites australis</i>	99 ± 1	Matamoros and Bayona (2006)	

concentrations of antibiotics in aquatic organisms are correlated with their habits, their position in the food chain, and vary in fish and shrimp from different pelagic layers, depending on their location in the aquatic environment (Li et al., 2012b). In a previous study, sediments adsorbed with antibiotics were collected and used to construct an ecosystem to cultivate zebrafish (Chen et al., 2017a). The presence of antibiotics was detected in the zebrafish, suggesting bioconcentration of antibiotics in aquatic organisms. Fish in wild water environments were tested for antibiotic levels and antibiotic

levels increased progressively from herbivorous to omnivorous to carnivorous, possibly *via* food chain enrichment (Tang et al., 2020). Antibiotics with different properties showed tissue specificity in aquatic products, suggesting significant differences in bioaccumulation factors between antibiotics (Liu et al., 2014; Zhao et al., 2015; Zhao et al., 2016a). Bioaccumulation and the different metabolic pathways of different aquatic organisms lead to a more complex accumulation of antibiotics in aquatic organisms. With the improvement in living standards, there is an increasing demand for aquatic products. The

TABLE 8 | Antibiotic-degrading bacterial strains reported in the recent three years.

Antibiotics	Bacterial species	Concentration (mg/L)	Removal rate (%)	Sources	References	
β -lactam	Cephalosporin	<i>Achromobacter</i> sp. YF-1	30	92.71 (7 days)	Waste medicine residue	Zhang et al. (2019a)
Sulfonamides	Sulfamethoxazole	<i>Shewanella oneidensis</i> MR-1	10	97.9 (3 days)	Laboratory	Mao et al. (2018)
	Sulfamethoxazole	<i>Shewanella</i> sp. MR-4	10	100 (3 days)	Laboratory	Mao et al. (2018)
	Sulfamethoxazole	<i>Pseudomonas mandelii</i> McBPA4	50	73 (15 days)	Laboratory	Reis et al. (2018)
	Sulfamethoxazole	<i>Acinetobacter</i> sp. W1	5–240	100 (10 h)	Activated sludge	Wang and Wang (2018)
	Sulfamethoxazole	<i>Ochrobactrum</i> sp. SMX-PM1-SA1	5	45.2 (8 days)	Wastewater	Zhang et al. (2019c)
	Sulfamethoxazole	<i>Labrys</i> sp. SMX-W11	5	62.2 (8 days)	Activated sludge	Mulla et al. (2018)
	Sulfamethoxazole	<i>Gordonia</i> sp. SMX-W2-SCD14	5	51.4 (8 days)	Pig manure	Mulla et al. (2018)
	Sulfamethoxazole	<i>Achromobacter</i> sp. JL9	50	79.45 (120 h)	Pharmaceutical wastewater	Liang et al. (2019)
	Sulfamethoxazole	<i>Acinetobacter</i> sp.	30	100 (5 h)	Microbiological culture collection	Wang et al. (2018a)
	Sulfadimidine	<i>Bacillus cereus</i> J2	50	100 (36 h)	Municipal sewage	Zhang et al. (2019c)
	Sulfamethazine	<i>Acinetobacter</i> sp.	30	100 (10 h)	Microbiological culture collection	Wang et al. (2018a)
	Sulfadiazine	<i>Acinetobacter</i> sp.	30	100 (10 h)	Microbiological culture collection	Wang et al. (2018a)
Tetracyclines	Tetracycline	<i>Raoultella</i> sp. XY-1	20	70.68 (8 days)	Pig farm sediment	Wu et al. (2018)
	Tetracycline	<i>Klebsiella</i> sp. SQY5	10–30	67.32 (92 h)	Municipal sludge	Shao et al. (2018a)
	Tetracycline	<i>Achromobacter</i> sp. TJ-2#	50	63.9 (3 days)	Contaminated soil	Cheng et al. (2017b)
	Oxytetracycline	<i>Pseudomonas</i> sp. T4	100	26.88 (7 days)	Livestock manure	Meng et al. (2018)
	Oxytetracycline	<i>Achromobacter</i> sp. TJ-2#	50	58.3 (3 days)	Contaminated soil	Cheng et al. (2017b)
	Oxytetracycline	<i>Ochrobactrum</i> sp. KSS10	30	63.33 (4 days)	Municipal sludge	Shao et al. (2018b)
	Aureomycin	<i>Achromobacter</i> sp. TJ-2#	50	65.5 (3 days)	Contaminated soil	Cheng et al. (2017b)
Fluoroquinolones	Norfloxacin	<i>Staphylococcus caprae</i> NOR-36	5	92.6 (10 days)	Pharmaceutical wastewater	Fu et al. (2017)
	Ofloxain	<i>Labrys portucalensis</i> F11	0.45	34.6 (28 days)	Fluorobenzene	(Maia et al., 2018)
	Ofloxain	<i>Rhodococcus</i> sp. FR1	0.45	39.3 (28 days)	Fluorobenzene	(Maia et al., 2018)
	Ciprofloxacin	<i>Thermus thermophiles</i> C419	5	57 (5 days)	Pharmaceutical sludge	(Pan et al., 2017)
	Ciprofloxacin	<i>Enterobacter</i> sp. (KM504128)	5	96 (14 days)	Hospital effluent water	Liyanage and Manage (2018)
	Ciprofloxacin	<i>Lactobacillus gesseri</i> . (KM4055978)	5	100 (14 days)	Hospital effluent water	Liyanage and Manage (2018)
	Ciprofloxacin	<i>Bacillus</i> sp. (KM504129)	5	74 (14 days)	Hospital effluent water	Liyanage and Manage (2018)
	Ciprofloxacin	<i>Bradyrhizobium</i> sp. GLC_01	0.05	70.4 \pm 7.4 (8 days)	Wastewater	Nguyen et al. (2018)
Macrolides	Tylosin	<i>Achromobacter</i>	50	96.08 (56 days)	Spinach soil	Zhang et al. (2018c)

government should strengthen the regulation of antibiotic content in aquatic products. There is also a need to strengthen the regulation of fishery drugs and scientific use of drugs and improve the code of practice and standards.

DEGRADATION OF ANTIBIOTICS

Antibiotic pollution is becoming increasingly serious globally. Although countries with severe antibiotic pollution have introduced corresponding policies, they have come too late and/or are inadequate to solve the problem (Kara, 2019). Currently, researchers are in the process of developing environmentally friendly alternatives to antibiotics to reduce the use of antibiotics. At the same time, owing to the excessive antibiotic content in the aquatic environment, researchers have

developed various antibiotic treatment techniques to degrade antibiotics. These methods can be roughly divided into the following categories: physical adsorption, chemical oxidation, photodegradation, and biodegradation. The general characteristics of various methods of removing antibiotics from water bodies are shown in Table 6.

Physical Removal of Antibiotics

The removal of antibiotics from the aquatic environment can be achieved by adsorbing the antibiotics on an adsorbent and then recovering the adsorbent loaded with antibiotics. Existing physical methods include physical adsorption, membrane filtration, and precipitation. However, the physical methods can only separate the antibiotics from the environment but not degrade them, and subsequent treatment is necessary.

TABLE 9 | Antibiotic-degrading fungi reported in the recent 5 years.

Antibiotics	Fungus	Concentration (mg/L)	Removal rate (%)	Degradation enzyme	References	
Sulfonamides	Sulfadiazine	<i>Fusarium solani</i> KS256	1.5	18.53 (7 days)	—	Wang et al. (2018b)
	Sulfamethoxazole	<i>Pycnoporus sanguineus</i>	10	100 (2 days)	Lac P450	Gao et al. (2017a)
	Sulfamethoxazole	<i>Phanerochaete Chrysosporium</i>	10	63.3 (8 days)	MnP and LiP P450	Gao et al. (2017a)
	Sulfamethoxazole	<i>Phoma sp.</i> UHH5-1-03	10	57 (168 h)	Lac	Hofmann and Schlosser (2016)
	Sulfamethoxazole	<i>Trametes versicolor</i> ATCC 42530	10	90–94 (30 days)	—	Aydin (2016)
	Sulfamethoxazole	<i>Bjerkandera adusta</i> ATCC 28314	10	90–94 (30 days)	—	Aydin (2016)
	Sulfamethoxazole	<i>Achromobacter denitrificans</i> strain PR1	150	91(51 h)	—	Nguyen et al. (2018)
Fluoroquinolones	Ciprofloxacin	<i>Pleurotus ostreatus</i>	500	95.07	MnP	Singh et al. (2017)
	Norfloxacin	<i>Penicillium janthinellum</i> KS272	1.5	10.59 (8 days)	—	Wang et al. (2018b)
	Ciprofloxacin	<i>Pycnoporus sanguineus</i>	10	98.5 (2 days)	Lac P450	Gao et al. (2017a)
	Norfloxacin	<i>Pycnoporus sanguineus</i>	10	96.4 (2 days)	Lac P450	Gao et al. (2017a)
	Ciprofloxacin	<i>Phanerochaete Chrysosporium</i>	10	64.5 (8 days)	MnP and LiP P450	Gao et al. (2017a)
	Norfloxacin	<i>Phanerochaete Chrysosporium</i>	10	73.2 (8 days)	MnP and LiP P450	Gao et al. (2017a)
	Norfloxacin	<i>Irpex lacteus</i>	10	100 (10 days)	Lac P450	Čvančarová et al. (2015)
	Norfloxacin	<i>Trametes versicolor</i>	10	85 (14 days)	MnP and MIP	Čvančarová et al. (2015)
	Ofloxacin	<i>Irpex lacteus</i>	10	100 (10 days)	MnP and MIP	Čvančarová et al. (2015)
	Ciprofloxacin	<i>Irpex lacteus</i>	10	100 (10 days)	Lac and MnP and MIP	Čvančarová et al. (2015)
Tetracyclines	Ciprofloxacin	<i>Pleurotus ostreatus</i>	10	60 (14 days)	Lac	Čvančarová et al. (2015)
	Oxytetracycline	<i>Fusarium verticilloides</i> KS248	1.5	34.63 (7 days)	—	Wang et al. (2018b)
	Oxytetracycline	<i>Penicillium janthinellum</i> KS272	1.5	40.29 (7 days)	—	Wang et al. (2018b)
	Oxytetracycline	<i>T. harzianum</i>	250	92 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Oxytetracycline	<i>T. deliquescens</i>	250	85 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Oxytetracycline	<i>P. crustosum</i>	250	83 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Tetracycline	<i>Phanerochaete chrysosporium</i>	10	80 (3 days)	Lip, mnp	Qing et al. (2018)
	Tetracycline	<i>Trichoderma harzianum</i>	250	92 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Tetracycline	<i>Trichoderma deliquescens</i>	250	85 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Tetracycline	<i>Penicillium crustosum</i>	250	83 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Tetracycline	<i>Rhodotorula mucilaginosa</i>	250	73 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Tetracycline	<i>Talaromyces atroseus</i>	250	72 (21 days)	—	Ahumada-Rudolph et al. (2016)
	Beta-lactam	Oxacillin	<i>Leptosphaerulina sp.</i>	16	100 (6 days)	Lac and mnp and lip
Cloxacillin		<i>Leptosphaerulina sp.</i>	17.5	100 (6 days)	Lac and mnp and lip	Copete-Pertuz et al. (2018)
Dicloxacillin		<i>Leptosphaerulina sp.</i>	19	100 (6 days)	Lac and mnp and lip	Copete-Pertuz et al. (2018)
Cephadroxy		<i>Leptosphaerulina sp.</i> CECT20913	15.2	100 (15 days)	Lac and mnp	Pérez Grisales et al. (2019)
Cephadroxy		<i>Trametes versicolor</i> ATCC 42530	6	100 (15 days)	Lac and mnp	Pérez Grisales et al. (2019)

Notes: Lac: laccase; LiP: lignin peroxidase; MnP: manganese peroxidase; MIP: manganese-independent peroxidase; CGMCC: China General Microbiological Culture Collection Center.

Physical Adsorption

Physical adsorption is the adsorption of antibiotic molecules on the adsorbent through intermolecular forces. Commonly used adsorbents include activated carbon, modified activated carbon, and other molecular sieve pore structure substances. Ahmed and Theydan (2014) used microwave technology to prepare activated carbon and had high adsorption rates for both ciprofloxacin (CIP) and norfloxacin. Choi et al. (2008) successfully used granular activated carbon. In a different study, Chen and

Huang (2010) analyzed the strong adsorption of alumina to three tetracycline antibiotics (chlortetracycline, oxytetracycline, and tetracycline). The efficiency of an adsorbent is related to the pH of the solution. Adsorbents are widely used in wastewater management because they not only adsorb small molecules, such as antibiotics, but also some heavy metal ions and toxic substances such as dyes. Physical adsorption is a low cost method characterized by simple preparation of the adsorbent, no high technical requirements, simple operation, large specific

TABLE 10 | Antibiotic enzyme systems.

Antibiotics		Enzyme	pH	Temperature (°C)	Time	Removal rate (%)	References
Sulfonamides	Sulfamethoxazole	Laccase-syringaldehyde	6	25	<1 h	100	Kumar et al. (2005)
	Sulfamethoxazole	Laccase-acetosyringone	6	25	<1 h	100	Kumar et al. (2005)
	Sulfonamide*	Laccase-syringaldehyde	6	25	180 min	>97	Ding et al. (2016)
	Sulfadimethoxine	Laccase-2-2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt	4.1	30	30 min	85	Weng et al. (2011)
	Sulfadimethoxine	Laccase-violuric acid	4.1	30	30 min	81	Weng et al. (2011)
	Sulfamonomethoxine	Laccase-2-2'-azino-bis-(3-ethylbenzothiazoline-7-sulfonic acid) diammonium salt	4.1	30	30 min	67	Weng et al. (2011)
	Sulfamonomethoxine	Laccase-violuric acid	4.1	30	30 min	82	Weng et al. (2011)
	Sulfadimethoxine	Laccase-4-hydroxybenzyl alcohol	4.1	30	330 min	67	Weng et al. (2011)
	Sulfadimethoxine	Laccase-syringaldehyde	4.1	30	330 min	89–90	Weng et al. (2011)
	Sulfamonomethoxine	Laccase-5-hydroxybenzyl alcohol	4.1	30	330 min	70	Weng et al. (2011)
	Sulfamonomethoxine	Laccase-syringaldehyde	4.1	30	330 min	83	Weng et al. (2011)
Fluoroquinolones	Sulfamethoxazole	Laccase	4.5	30	24 h	50	Guo et al. (2014)
	Norfloxacin	Chloroperoxidase (CPO)-H ₂ O ₂	5	25	25 min	82.18	Zhao et al. (2017)
	Ciprofloxacin	Combi-CLEA (laccase and versatile peroxidase and glucose oxidase)	3	30	72 h	80/90	Touahar et al. (2014)
Tetracyclines	Fluoroquinolone*	Laccase-syringaldehyde + soil	6	25	180 min	>95	Ding et al. (2016)
	Trimethoprim	Combi-CLEA (laccase and versatile peroxidase and glucose oxidase)	3	30	72 h	50–70	Touahar et al. (2014)
	Tetracycline*	Laccase-syringaldehyde + soil	6	25	180 min	>95	Ding et al. (2016)
	Tetracycline	Laccase	7	20	18 h	78	Llorca et al. (2014)
	Tetracycline	Crude lignin peroxidase-veratryl alcohol	4.2	37	30 min	99	Wen et al. (2009)
	Tetracycline	Crude lignin peroxidase	3	37	30 min	92	Xingxing et al., (2016)
Macrolides	Erythromycin	EreB esterase	7	37	16 h	52	Llorca et al. (2014)

surface area, and strong capacity for antibiotic adsorption. However, due to weak intermolecular interaction, the adsorbed antibiotics can easily escape under the influence of the external environment and cause secondary pollution, and is thus limited in its use to cases with low antibiotic concentrations.

Membrane Filtration

Membrane separation technology uses micro- and nano-porous membranes to intercept or reverse osmosis of antibiotics in water for purification purposes. In practice, membrane separation is commonly used in conjunction with other methods to remove antibiotics from the aquatic environment. Wang et al. (2017a) studied the removal efficiency and influencing factors of tetracycline in water using a magnetic flocculation-membrane separation technique. Yang et al. (2020) made membrane bioreactors (MBRs) more effective for antibiotic treatment by adding rice straw to improve denitrification. In a study by Pérez and Barceló (2008), a laboratory-scale membrane bioreactor achieved a 56% elimination of diclofenac metabolite 4'-hydroxydiclofenac. The use of membrane filtration is a

physical process that does not add any chemical reagents, is green, and has good selective filtration. However, because of the small size of the antibiotic molecule and the tendency of other contaminants to clog the pore size, the membrane module needs to be replaced frequently, which is costly.

Degradation of Antibiotics by Photolysis

The separation of electrons and holes generated by semiconductor photocatalysts under light excitation leads to the generation of a large number of oxygen radicals in aquatic environments, thus oxidizing any present antibiotics. Titanium oxide has a high degradation rate for antibiotics in water, however, owing to the narrow spectral absorption of pure TiO₂, researchers often modify it to efficiently degrade antibiotics in wastewater. Mushtaq et al. (2020) used titanium isopropoxide as a titanium precursor to synthesize peptide-based nanoparticles to study the degradation of NOR. Mountassir et al. (2020) constructed recyclable LDH-TiO₂ nanocomposites to degrade sulfamethyisoxazole under UV radiation, where TiO₂ can be reused, to reduce the threat to

water resources. Furthermore, researchers are developing new photoelectric systems and explore the use of other metal mineral salts as catalysts to degrade antibiotics. Chang et al. (2017a) constructed a new photoelectric catalytic (PEC) coupled electroenzyme-catalyzed (EEC) oxidation system that degraded up to 98.7% chloramphenicol within 10 h. Eswar et al. (2017) investigated the performance of reticulated CuO photocatalytic degradation of tetracycline in water. Cao et al. (2018) loaded AgPO₄-modified BiVO₄ on a photoanode on conductive glass, which effectively degraded levofloxacin in water. Photodegradation, a widely used method for the degradation of antibiotics, is green and environmentally friendly, relying on water molecules to provide hydroxyl radicals and oxygen radicals to degrade antibiotics, thus avoiding the possibility of secondary pollution. However, because of the high construction cost of photoelectrodes, it can only be used short-range, which comes with certain limitations. At the same time, some suspended solids and deep pigments in the wastewater obstruct the passage of light and negatively affect the photocatalytic effect.

Chemical Oxidative Degradation of Antibiotics

Chemical oxidation is the degradation of antibiotics through free radicals produced by a chemical reaction that react directly with the antibiotic, causing its chemical bonds to break or decompose. However, this type of method produces a large amount of secondary pollution.

Ji et al. (2015), Yan et al. (2015) used thermal activation of peroxyxynitrite to produce sulfate radicals to effectively degrade sulfonamide antibiotics, but the effect is not very stable. Gaffney et al. (2015), Nassar et al. (2018) found that chlorination and oxidation selectively removed sulfonamide antibiotics from water, but the degradation effect was greatly influenced by the concentration of the antibiotics and pH.

Compared with earlier oxidative degradation by strong oxidants, Fenton oxidation has greatly reduced the chemical pollution of the environment (Tunç et al., 2012; Tunç et al., 2013; Le et al., 2016; Weng et al., 2020). It can effectively oxidize and remove the difficult-to-degrade organic substances that cannot be removed by traditional wastewater treatment technology. Ioannou-Ttofa et al. (2018) used light illumination combined with the Fenton oxidation technique to degrade ampicillin in water, and showed that the pH had a great influence on the degradation result. The degradation rate of ampicillin increased with an increase in solution pH under acidic conditions.

Biodegradation of Antibiotics

Biodegradation of antibiotics is the use of microorganisms, microbes, and enzymes to break down antibiotics in the environment. It generally does not cause secondary pollution, can be used in a variety of environments, and is an environmentally friendly disposal method.

Plant Adsorption

Plants take up antibiotics from river water and bottom sediments through roots, stems, and leaves, and then transport them

through transpiration or degradation by microorganisms enriched by the roots (Susarla et al., 2002), thus reducing the content of pollutants in the aqueous environment. Plant removal of antibiotics is currently performed mainly by the construction of plant floating beds, artificial wetlands, and other environmental management technologies. Because of their low cost and ease of operation, artificial floating beds are more common than artificial wetlands (Figure 6), even though artificial wetlands can simultaneously deal with a variety of environmental pollution problems and have self-healing functions that can be used for long periods. As shown in Table 7, the type of antibiotic that can be removed from the water column and the antibiotic removal efficiency vary for different plants.

Degradation of Antibiotics Using Activated Sludge

Activated sludge is a collective term for communities of microorganisms and the organic and inorganic materials to which they are attached, and is used for biosorption of antibiotics, biodegradation of antibiotics, and flocculation. The complex microorganisms in the activated sludge form a complex food chain with organic nutrients in the wastewater, and the degradation of antibiotics is achieved through the action of the microbial community. Composting with activated sludge removes contaminants through adsorption and microbial biodegradation. Studies have shown (Zhang et al., 2019b; Zhu et al., 2020) that antibiotics can be removed either by microbial nitrification (autotrophic biodegradation) or by microbial chemical oxygen demand (COD) degradation (heterotrophic biodegradation) in activated sludge.

Terzic et al. (2018) found that activated sludge from a municipal wastewater treatment plant was able to degrade three major macrolides (erythromycin, clarithromycin, and azithromycin) and evaluated their toxicity. Their results showed that the harmful effects of the treated effluent were greatly reduced. Radjenovic et al. (2009) found that charged activated sludge influenced the adsorption of environmental quinolone antibiotics. However, while the adsorption was improved, the effect was not stable. Activated sludge for the degradation of antibiotics is generally derived from biopharmaceutical or hospital wastewater and significantly reduces post-degradation toxicity after activated sludge treatment. However, this method is highly dependent on environmental factors such as pH, temperature, dissolved oxygen, nutrients, and toxic substances, as well as the composition and proportion of the microorganisms, which influence the degradation time. Under low dissolved oxygen conditions, irritating gases such as ammonia or sulfur dioxide are easily produced, and the proportion of nutrients in the wastewater needs to be adjusted frequently; otherwise, the degradation efficiency is low.

The use of activated sludge to decompose antibiotics could have some disadvantages. For example, bacterial fermentation in activated sludge may occur to complete the decomposition of antibiotics. The exposure of bacteria to antibiotics may then lead to the production and proliferation of ARGs, resulting in the emergence of novel types of genetic pollutants (Zeng et al., 2019)

Degradation by Microbial Strains

As a result of prolonged exposure to antibiotics, strains of bacteria become resistant to antibiotics and may even break them down. The biodegradation of antibiotics is dominated by microbial decomposition. However, the antibiotic degradation ability of strains is influenced by many factors such as the antibiotic species, strain type, carbon source, nitrogen source, temperature, and wastewater components (heavy metal ions, COD, etc.,). In recent years, many bacterial strains with antibiotic degradation abilities have been isolated through screening, enrichment, and domestication, and mainly degrade sulfonamides and tetracyclines. This is most likely due to the fact that these two types of antibiotics are more likely to be adsorbed onto sediment and thus remain in a stationary environment for longer periods (Mulla et al., 2018). **Table 8** lists the antibiotic-degrading bacterial strains reported in the literature over the last three years.

The microorganisms that degrade antibiotics can be divided into single and mixed strains, some of which are listed in Martins et al. (2018) demonstrated for the first time that sulfate-reducing flora could remove CIP, and Cordova-Kreylos and Scow (2007) observed that exposing anaerobic sediments to the antibiotic CIP sulfate-reducing bacteria (SRB) is advantageous. In addition, there have been reports that bacteria can degrade antibiotics under sulfate-reducing conditions (Jia et al., 2017) and that nitrate reduction has been used successfully in microbial remediation, where denitrifying bacteria can effectively degrade enrofloxacin and ceftiofur (Alexandrino et al., 2017) as well as CIP. Antibiotic-degrading flora are also present in many estuarine sediments enriched in antibiotics; Chang and Ren (2015) isolated tetracycline antibiotic-degrading flora in sediments of the Eren River estuary, and Harrabi et al. (2018) enriched the flora of the Douro River estuary and achieved a greater than 95% degradation for oxytetracycline and enrofloxacin.

Fungi are more tolerant to high concentrations of pollutants than bacteria and, therefore, are more advantageous in the degradation of antibiotics. Numerous studies have shown that it is feasible to use fungi to degrade antibiotics present in the environment. In **Table 9**, the antibiotic-degrading fungi reported in the literature during the last 5 years are listed.

Enzymatic Degradation

Microorganisms can produce enzymes that degrade antibiotics, such as β -lactamases, which can cleave the β -lactam rings of cyanotoxins and cephalosporins. Based on the substrate specificity of β -lactamases, they can be roughly divided into three categories: penicillinases, cephalosporinases, and oxime-type cephalosporinases. Penicillin enzymes easily decompose penicillin antibiotics, while cephalosporin enzymes have a higher activity in decomposing cephalosporin antibiotics, and the oxime cephalosporin enzymes have a decomposing effect on both penicillin and cephalosporin, but are especially good at decomposing oxime cephalosporin. To efficiently degrade antibiotics, enzyme systems can be constructed. **Table 10** lists the enzyme systems that have been used to degrade antibiotics in recent years.

The construction of various enzyme systems and the use of immobilized enzymes to degrade antibiotics, considered a breakthrough in the field of environmental management, was motivated by the fact that enzymes are easily inactivated in the environment and cannot be used in large quantities in practical applications. Gao et al. (2017b) using magnetic nanoparticles Fe_3O_4 to immobilize β -lactamase to degrade penicillin, the efficiency remained above 95% after 35 times of repeated use; Zhang et al. (2020a) used *in situ* immobilized laccase to degrade tetracycline and ampicillin and achieved a degradation efficiency in water close to 100%. Simón-Herrero et al. (2019) found that laccase immobilized on polyimide gels used to remove carbamazepine yielded a degradation efficiency of 74%. In a different study, Zdarta et al. (2019) successfully degraded tetracycline by laccase immobilized with electrospun materials using 1-hydroxybenzotriazole as a medium. For degradation experiments, Becker et al. (2017) constructed an enzyme membrane reactor using a mixture of immobilized laccase and eugenol for the degradation of 38 antibiotics. Their results showed that after 24 h the reactor degraded 32 types of antibiotics with a degradation rate of greater than 50%.

At present, the existing enzymes are mainly β -lactamase types for the degradation of lactam antibiotics, laccase, and other strong oxidative enzymes for the nonselective oxidative degradation of antibiotics. Due to the rapid development of immobilized materials, an increasing number of enzymes are immobilized and are already used in actual sites to manage antibiotics pollution (Shao et al., 2019; Liang and Hu, 2020; Shakerian et al., 2020; Zhang et al., 2020a), resulting in an improvement of the stability of the enzymes and the recycling and reuse of them, thus reducing the cost. Over the past two years, immobilized lacquer enzymes have been applied to the degradation of antibiotics, and some other strongly oxidizing enzymes have gradually entered the view of the general researcher and are applied to oxidative degradation of antibiotics by immobilization.

SUMMARY AND OUTLOOK

Antibiotics have greatly polluted the environment globally. Among the prevalent antibiotic pollution treatments, physical adsorption cannot degrade antibiotics, chemical oxidation is likely to cause secondary pollution, photodegradation is expensive. Biodegradation of antibiotics, however, is attracting increasing attention because of its low cost, easy operation, and lack of secondary pollution. Nevertheless, both microbial degradation and activated sludge degradation will inevitably lead to the proliferation of ARGs. Therefore, using purified antibiotic-degrading enzymes for the degradation of antibiotics poses a good alternative. Synthesizing related enzymes *in vitro* or constructing engineered bacteria to produce enzymes would reduce the cost of this approach, making it even more attractive. Therefore, enzyme degradation is becoming the future mainstream of environmental management. The main remaining problem is whether the antibiotic degradation products have toxicity. Although the degradation products of

antibiotics are tested for bacterial toxicity, whether there may be a long-term toxicity problem has yet to be determined. However, it is undeniable that the toxicity of enzymatic antibiotics will be greatly reduced. Once the toxicity problem is solved, antibiotic-degrading enzymes may be used in a variety of wastewater treatments.

Antibiotics in the environment can be enriched in humans through the food chain, and they can be very harmful to young children and pregnant women. In addition, antibiotic contamination increases the development of superbugs. However, there is a lack of mandatory standards for the limits of antibiotic fugitive levels in the surface water. Thus, there is an urgent need to control antibiotics in water bodies. China's vast territory has a diverse climate, a diverse industrial layout, and unbalanced economic development. All the factors above influence the distribution of antibiotics in China, and these factors make it challenging for governments to control antibiotics. In recent years, China has attached great importance to the issue of antibiotic contamination, and the government has made significant improvements in antibiotic stewardship; however, there are still some shortcomings, such as, the antibiotic regulatory system and antibiotic management-related standards are inadequate to effectively combat antibiotics

pollution. In addition, factory emissions do not meet safety standards. Furthermore, there are no institutions specializing in antibiotic use and management to monitor the use of antibiotics and subsequent pollution management. Finally, scientific guidance on drug use is still required to discourage and prevent antibiotic abuse.

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WT and LM conceived the idea of the review, LZ collected literature, CL and LT wrote the manuscript. All authors contributed to the article.

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REFERENCES

- Ahmed, M. J., and Theydan, S. K. (2014). Fluoroquinolones Antibiotics Adsorption onto Microporous Activated Carbon from Lignocellulosic Biomass by Microwave Pyrolysis. *J. Taiwan Inst. Chem. Eng.* 45, 219–226. doi:10.1016/j.jtice.2013.05.014
- Ahumada-Rudolph, R., Novoa, V., Sáez, K., Martínez, M., Rudolph, A., Torres-Díaz, C., et al. (2016). Marine Fungi Isolated from Chilean Fjord Sediments Can Degrade Oxytetracycline. *Environ. Monit. Assess.* 188. doi:10.1007/s10661-016-5475-0
- Alexandrino, D. A. M., Mucha, A. P., Almeida, C. M. R., Gao, W., Jia, Z., and Carvalho, M. F. (2017). Biodegradation of the Veterinary Antibiotics Enrofloxacin and Cefotiofur and Associated Microbial Community Dynamics. *Sci. Total Environ.* 581–582, 359–368. doi:10.1016/j.scitotenv.2016.12.141
- Aydin, S. (2016). Enhanced Biodegradation of Antibiotic Combinations via the Sequential Treatment of the Sludge Resulting from Pharmaceutical Wastewater Treatment Using White-rot Fungi *Trametes versicolor* and *Bjerkandera Adusta*. *Appl. Microbiol. Biotechnol.* 100, 6491–6499. doi:10.1007/s00253-016-7473-0
- Bao, Y., Li, F. W., and Wen, D. H. (2021). Antibiotic Contamination in Mariculture in China. *Mar. Environ. Sci.* 40, 294–302.
- Baran, W., Adamek, E., Ziemiańska, J., and Sobczak, A. (2011). Effects of the Presence of Sulfonamides in the Environment and Their Influence on Human Health. *J. Hazard. Mater.* 196, 1–15. doi:10.1016/j.jhazmat.2011.08.082
- Becker, D., Rodríguez-Mozaz, S., Insa, S., Schoevaert, R., Barceló, D., de Cazes, M., et al. (2017). Removal of Endocrine Disrupting Chemicals in Wastewater by Enzymatic Treatment with Fungal Laccases. *Org. Process. Res. Dev.* 21, 480–491. doi:10.1021/acs.oprd.6b00361
- Ben, W., Pan, X., and Qiang, Z. (2013). Occurrence and Partition of Antibiotics in the Liquid and Solid Phases of Swine Wastewater from Concentrated Animal Feeding Operations in Shandong Province, China. *Environ. Sci. Process. Impacts* 15, 870–875. doi:10.1039/c3em30845f
- Bengtsson-Palme, J. (2017). Antibiotic Resistance in the Food Supply Chain: where Can Sequencing and Metagenomics Aid Risk Assessment? *Curr. Opin. Food Sci.* 14, 66–71. doi:10.1016/j.cofs.2017.01.010
- Bilal, M., Ashraf, S. S., Barceló, D., and Iqbal, H. M. N. (2019). Biocatalytic Degradation/redefining “Removal” Fate of Pharmaceutically Active Compounds and Antibiotics in the Aquatic Environment. *Sci. Total Environ.* 691, 1190–1211. doi:10.1016/j.scitotenv.2019.07.224
- Bitchava, K., and Nengas, I. (2010). Antibacterial Drugs in Products Originating from Aquaculture: Assessing the Risks to Public Welfare. *Medit. Mar. Sci.* 11, 33–41. doi:10.12681/mms.89
- Bo, D. (2017). *Study on Photocatalytic Degradation of Antibiotic Wastewater*. Management & Technology of SME, 138–140. doi:10.3969/j.issn.1673-1069.2017.15.067
- Brain, R. A., Hanson, M. L., Solomon, K. R., and Brooks, B. W. (2008). Aquatic Plants Exposed to Pharmaceuticals: Effects and Risks. *Rev. Environ. Contam. T.* 192, 67–115. doi:10.1007/978-0-387-71724-1_3
- Brain, R. A., Johnson, D. J., Richards, S. M., Sanderson, H., Sibley, P. K., and Solomon, K. R. (2004). Effects of 25 Pharmaceutical Compounds to Lemna Gibba Using a Seven-Day Static-Renewal Test. *Environ. Toxicol. Chem.* 23, 371–382. doi:10.1897/02-576
- Briones, R. M., Sarmah, A. K., and Padhye, L. P. (2016). A Global Perspective on the Use, Occurrence, Fate and Effects of Anti-diabetic Drug Metformin in Natural and Engineered Ecosystems. *Environ. Pollut.* 219, 1007–1020. doi:10.1016/j.envpol.2016.07.040
- Cao, D., Wang, Y., Qiao, M., and Zhao, X. (2018). Enhanced Photoelectrocatalytic Degradation of Norfloxacin by an Ag 3 PO 4/BiVO 4 Electrode with Low Bias. *J. Catal.* 360, 240–249. doi:10.1016/j.jcat.2018.01.017
- Cao, J., Liu, F., Liu, S., Wang, J., Zhu, B., Shi, Y., et al. (2021). Identification of Antibiotic Resistance Genes and Associated mobile Genetic Elements in Permafrost. *Sci. China Life Sci.* 1–4.
- Chang, B.-V., and Ren, Y.-L. (2015). Biodegradation of Three Tetracyclines in River Sediment. *Ecol. Eng.* 75, 272–277. doi:10.1016/j.ecoleng.2014.11.039
- Chen, H., Liu, S., Xu, X.-R., Diao, Z.-H., Sun, K.-F., Hao, Q.-W., et al. (2018). Tissue Distribution, Bioaccumulation Characteristics and Health Risk of Antibiotics in Cultured Fish from a Typical Aquaculture Area. *J. Hazard. Mater.* 343, 140–148. doi:10.1016/j.jhazmat.2017.09.017
- Chen, H., Liu, S., Xu, X.-R., Liu, S.-S., Zhou, G.-J., Sun, K.-F., et al. (2015). Antibiotics in Typical marine Aquaculture Farms Surrounding Hailing Island, South China: Occurrence, Bioaccumulation and Human Dietary Exposure. *Mar. Pollut. Bull.* 90, 181–187. doi:10.1016/j.marpolbul.2014.10.053

- Chen, J., Ying, G. G., Wei, X. D., Liu, Y. S., Liu, S. S., Hu, L. X., et al. (2016). Removal of Antibiotics and Antibiotic Resistance Genes from Domestic Sewage by Constructed Wetlands: Effect of Flow Configuration and Plant Species. *Sci. Total Environ.* 571, 974–982. doi:10.1016/j.scitotenv.2016.07.085
- Chen, J., Tong, T., Jiang, X., and Xie, S. (2020a). Biodegradation of Sulfonamides in Both Oxidic and Anoxic Zones of Vertical Flow Constructed Wetland and the Potential Degraders. *Environ. Pollut.* 265, 115040. doi:10.1016/j.envpol.2020.115040
- Chen, L., Li, H., Liu, Y., Cui, Y., Li, Y., and Yang, Z. (2019). Distribution, Residue Level, Sources, and Phase Partition of Antibiotics in Surface Sediments from the Inland River: a Case Study of the Xiangjiang River, South-central China. *Environ. Sci. Pollut. Res.* 27, 2273–2286. doi:10.1007/s11356-019-06833-0
- Chen, Q., Guo, X., Hua, G., Li, G., Feng, R., and Liu, X. (2017). Migration and Degradation of Swine Farm Tetracyclines at the River Catchment Scale: Can the Multi-Pond System Mitigate Pollution Risk to Receiving Rivers?. *Environ. Pollut.* 220, 1301–1310. doi:10.1016/j.envpol.2016.11.004
- Chen, W.-R., and Huang, C.-H. (2010). Adsorption and Transformation of Tetracycline Antibiotics with Aluminum Oxide. *Chemosphere* 79, 779–785. doi:10.1016/j.chemosphere.2010.03.020
- Chen, W. P., Peng, C. W., Yang, Y., and Wu, Y. M. (2017b). [Distribution Characteristics and Risk Analysis of Antibiotic in the Groundwater in Beijing]. *Huan Jing Ke Xue* 38, 5074–5080. doi:10.13227/j.hj.kx.201704287
- Chen, Y., Cui, K., Huang, Q., Guo, Z., Huang, Y., Yu, K., et al. (2020b). Comprehensive Insights into the Occurrence, Distribution, Risk Assessment and Indicator Screening of Antibiotics in a Large Drinking Reservoir System. *Sci. Total Environ.* 716, 137060. doi:10.1016/j.scitotenv.2020.137060
- Chen, Y., Zhou, J. L., Cheng, L., Zheng, Y. Y., and Xu, J. (2017a). Sediment and Salinity Effects on the Bioaccumulation of Sulfamethoxazole in Zebrafish (*Danio rerio*). *Chemosphere* 180, 467–475. doi:10.1016/j.chemosphere.2017.04.055
- Cheng, D., Liu, X., Wang, L., Gong, W., Liu, G., Fu, W., et al. (2014). Seasonal Variation and Sediment-Water Exchange of Antibiotics in a Shallower Large lake in North China. *Sci. Total Environ.* 476–477, 266–275. doi:10.1016/j.scitotenv.2014.01.010
- Cheng, J., Du, H., Zhang, T., and Wang, W. (2017b). Isolation and Identification of Tetracyclines Degrading Bacteria. *J. Nucl. Agric. Sci.* 31, 884–888. doi:10.11869/j.jissn.100-8551.2017.05.0884
- Cheng, L., Liu, L., Yan, K., and Zhang, J. (2017a). Visible Light-Driven Photoelectrocatalysis Coupling with Electroenzymatic Process for Degradation of Chloramphenicol. *Chem. Eng. J.* 330, 1380–1389. doi:10.1016/j.cej.2017.07.170
- Choi, K.-J., Kim, S.-G., and Kim, S.-H. (2008). Removal of Antibiotics by Coagulation and Granular Activated Carbon Filtration. *J. Hazard. Mater.* 151, 38–43. doi:10.1016/j.jhazmat.2007.05.059
- Chuan, R., Yanan, S., Yinghui, W., Yuanyuan, Z., and Kefu, Y. (2018). Formation of Disinfection Byproducts from Sulfamethoxazole during Sodium Hypochlorite Disinfection of marine Culture Water. *Environ. Sci. Pollut. Res. International.* 25, 33196–33206. doi:10.1007/s11356-018-3278-2
- Conkle, J. L., Lattao, C., White, J. R., and Cook, R. L. (2010). Competitive Sorption and Desorption Behavior for Three Fluoroquinolone Antibiotics in a Wastewater Treatment Wetland Soil. *Chemosphere* 80, 1353–1359. doi:10.1016/j.chemosphere.2010.06.012
- Copete-Pertuz, L. S., Plácido, J., Serna-Galvis, E. A., Torres-Palma, R. A., and Mora, A. (2018). Elimination of Isoxazolyl-Penicillins Antibiotics in Waters by the Lignolytic Native Colombian Strain *Leptosphaerulina* Sp. Considerations on Biodegradation Process and Antimicrobial Activity Removal. *Sci. Total Environ.* 630, 1195–1204. doi:10.1016/j.scitotenv.2018.02.244
- Córdova-Kreylos, A. L., and Scow, K. M. (2007). Effects of Ciprofloxacin on Salt Marsh Sediment Microbial Communities. *ISME J.* 1, 585–595. doi:10.1038/ismej.2007.71
- Čvančarová, M., Filipová, A., and Cajthaml, T. (2015). Biotransformation of Fluoroquinolone Antibiotics by Lignolytic Fungi – Metabolites, Enzymes and Residual Antibacterial Activity. *Chemosphere* 136. doi:10.1016/j.chemosphere.2014.12.012
- Dai, H. (2019). *Analysis of Antibiotic Pollution Characteristics and Ecological Risk Assessment in Water Sources of Qingyuan City and Dongguan City*. Xi'an Polytechnic University. doi:10.1007/978-3-030-02874-9
- Dan, A., Dai, Y. N., Chen, C. X., Wang, S. Y., and Tao, R. (2013). Removal and Factors Influencing Removal of Sulfonamides and Trimethoprim from Domestic Sewage in Constructed Wetlands. *Bioresour. Technol.* 146, 363–370. doi:10.1016/j.biortech.2013.07.050
- Dethlefsen, L., McFall-Ngai, M., Relman, D. A., Dethlefsen, L., and McFall-Ngai, M. (2007). An Ecological and Evolutionary Perspective on Human-Microbe Mutualism and Disease. *Nature* 449, 811–818. doi:10.1038/nature06245
- Di, X., Cui, X., Sun, K., Zhang, K., and Huang, T. (2019). Determination of Antibiotics Residues in Drinking Water Sample by Solid-phase Extraction/high Performance Liquid Chromatography Tandem Mass Spectrometry. *Mod. Chem. Ind.* 39, 243–247. doi:10.16606/j.cnki.issn0253-4320.2019.12.051
- Dik, V. K., Van Oijen, M. G. H., Smeets, H. M., and Siersema, P. D. (2016). Frequent Use of Antibiotics Is Associated with Colorectal Cancer Risk: Results of a Nested Case-Control Study. *Dig. Dis. Sci.* 61, 255–264. doi:10.1007/s10620-015-3828-0
- Ding, H. (2018). *Study on the Characteristics of Antibiotics in Poyang Lake and the Adsorption and Degradation of Typical Antibiotics*. Wuhan, China: Wuhan University.
- Ding, H., Wu, Y., Zhang, W., Zhong, J., Lou, Q., Yang, P., et al. (2017). Occurrence, Distribution, and Risk Assessment of Antibiotics in the Surface Water of Poyang Lake, the Largest Freshwater lake in China. *Chemosphere* 184, 137–147. doi:10.1016/j.chemosphere.2017.05.148
- Ding, H., Wu, Y., Zou, B., Lou, Q., Zhang, W., Zhong, J., et al. (2016). Simultaneous Removal and Degradation Characteristics of Sulfonamide, Tetracycline, and Quinolone Antibiotics by Laccase-Mediated Oxidation Coupled with Soil Adsorption. *J. Hazard. Mater.* 307, 350–358. doi:10.1016/j.jhazmat.2015.12.062
- Dong, D., Zhang, L., Liu, S., Guo, Z., and Hua, X. (2016). Antibiotics in Water and Sediments from Liao River in Jilin Province, China: Occurrence, Distribution, and Risk Assessment. *Environ. Earth Sci.* 75, 1202. doi:10.1007/s12665-016-6008-4
- Dong, W., Xin, H., Hongbo, Z., Zhang, Y., Quan, X., and Mu, H. (2020). Research on the Pollution and Distribution Characteristics of Typical Antibiotics in Dalian Biliuhe Reservoir and River. *J. Dalian Univ. Technol.* 60, 119–127.
- Dubreil, E., Gautier, S., Fourmond, M.-P., Bessiral, M., Gaugain, M., Verdon, E., et al. (2017). Validation Approach for a Fast and Simple Targeted Screening Method for 75 Antibiotics in Meat and Aquaculture Products Using LC-MS/MS. *Food Additives & Contaminants: A* 34, 453–468. doi:10.1080/19440049.2016.1230278
- Dutta, J., and Mala, A. A. (2020). Removal of Antibiotic from the Water Environment by the Adsorption Technologies: a Review. *Water Sci. Technol.* 82, 401–426. doi:10.2166/wst.2020.335
- Eswar, N. K., Singh, S. A., and Madras, G. (2018). Photoconductive Network Structured Copper Oxide for Simultaneous Photoelectrocatalytic Degradation of Antibiotic (Tetracycline) and Bacteria (*E. coli*). *Chem. Eng. J.* 332, 757–774. doi:10.1016/j.cej.2017.09.117
- Fan, Y., Ji, Y., Kong, D., Lu, J., and Zhou, Q. (2015). Kinetic and Mechanistic Investigations of the Degradation of Sulfamethazine in Heat-Activated Persulfate Oxidation Process. *J. Hazard. Mater.* 300, 39–47. doi:10.1016/j.jhazmat.2015.06.058
- Fang, L., Wei, Q., Wang, Y., Yang, L., Li, Z., and Liu, J. (2017). Source and Distribution of Typical Antibiotics in the Upper Huangpu River, Shanghai. *Environ. Pollut. Control.* 39, 301–306. doi:10.15985/j.cnki.1001-3865.2017.03.015
- Feng, L., Cheng, Y., Feng, L., Zhang, S., and Liu, Y. (2017). Distribution of Typical Antibiotics and Ecological Risk Assessment in Main Waters of Three Gorges Reservoir Area Research of *Environ. Sci.* 30, 1031–1040. doi:10.13198/j.jissn.1001-6929.2017.02.33
- Feng, L., Cheng, Y., Zhang, Y., Li, Z., Yu, Y., Feng, L., et al. (2020). Distribution and Human Health Risk Assessment of Antibiotic Residues in Large-Scale Drinking Water Sources in Chongqing Area of the Yangtze River. *Environ. Res.* 185, 109386. doi:10.1016/j.envres.2020.109386
- Feng, M. J., Zhang, Q., Song, N. H., Pu, Y. Q., Yang, Z. B., Liu, Y. H., et al. (2019). [Occurrence Characteristics and Risk Assessment of Antibiotics in Source Water of the Nanjing Reach of the Yangtze River]. *Huan Jing Ke Xue* 40, 5286–5293. doi:10.13227/j.hj.kx.201905139

- Fernandes, J. P., Almeida, C. M. R., Pereira, A. C., Ribeiro, I. L., Reis, I., Carvalho, P., et al. (2015). Microbial Community Dynamics Associated with Veterinary Antibiotics Removal in Constructed Wetlands Microcosms. *Bioresour. Technology* 182, 26–33. doi:10.1016/j.biortech.2015.01.096
- Forsberg, K. J., Reyes, A., Wang, B., Selleck, E. M., Sommer, M. O. A., and Dantas, G. (2012). The Shared Antibiotic Resistome of Soil Bacteria and Human Pathogens. *Science* 337, 1107–1111. doi:10.1126/science.1220761
- Fouhy, F., Guinane, C. M., Hussey, S., Wall, R., Ryan, C. A., Dempsey, E. M., et al. (2012). High-Throughput Sequencing Reveals the Incomplete, Short-Term Recovery of Infant Gut Microbiota Following Parenteral Antibiotic Treatment with Ampicillin and Gentamicin. *Antimicrob. Agents Chemother.* 56, 5811–5820. doi:10.1128/AAC.00789-12
- Fu, B., Chen, L., Cai, T., Yang, Q., and Ding, D. (2017). Isolation and Characterization of Norfloxacin-Degrading Bacterium Strain NOR-36. *Acta Scientiae Circumstantiae*. 37, 576–584. doi:10.13671/j.hjlx.2016.0245
- Gaffney, V. d. J., Cardoso, V. V., Benoliel, M. J., and Almeida, C. M. M. (2016). Chlorination and Oxidation of Sulfonamides by Free Chlorine: Identification and Behaviour of Reaction Products by UPLC-MS/MS. *J. Environ. Manage.* 166, 466–477. doi:10.1016/j.jenvman.2015.10.048
- Gao, N., Liu, C.-X., Xu, Q.-M., Cheng, J.-S., and Yuan, Y.-J. (2018a). Simultaneous Removal of Ciprofloxacin, Norfloxacin, Sulfamethoxazole by Co-producing Oxidative Enzymes System of *Phanerochaete chrysosporium* and *Pycnoporus sanguineus*. *Chemosphere* 195, 146–155. doi:10.1016/j.chemosphere.2017.12.062
- Gao, X. J., Fan, X. J., Chen, X. P., and Ge, Z. Q. (2017b). Immobilized β -lactamase on Fe₃O₄ Magnetic Nanoparticles for Degradation of β -lactam Antibiotics in Wastewater. *Int. J. Environ. Sci. Technol.* 15, 2203–2212. doi:10.1007/s13762-017-1596-4
- Goldman, E. (2004). Antibiotic Abuse in Animal Agriculture: Exacerbating Drug Resistance in Human Pathogens. *Hum. Ecol. Risk Assess. Int. J.* 10, 121–134. doi:10.1080/10807030490281016
- Goulet, O. (2015). Potential Role of the Intestinal Microbiota in Programming Health and Disease: Figure 1. *Nutr. Rev.* 73 (Suppl. 1), 32–40. doi:10.1093/nutrit/nuv039
- Grenni, P., Ancona, V., and Barra Caracciolo, A. (2018). Ecological Effects of Antibiotics on Natural Ecosystems: A Review. *Microchemical J.* 136, 25–39. doi:10.1016/j.microc.2017.02.006
- Gujarathi, N. P., Haney, B. J., Park, H. J., Wickramasinghe, S. R., and Linden, J. C. (2005). Hairy Roots of *Helianthus Annuus*: A Model System to Study Phytoremediation of Tetracycline and Oxytetracycline. *Biotechnol. Prog.* 21, 775–780. doi:10.1021/bp0496225
- Guo, R., Wang, S., Chang, S., Wang, X., Zhao, X., Yang, G., et al. (2016). Distribution Characteristics of Antibiotics in Jiaying Drinking Water Source and Urban River. *Environ. Chem.* 35, 1842–1852. doi:10.7524/j.issn.0254-6108.2016.09.2016020401
- Guo, X.-l., Zhu, Z.-w., and Li, H.-l. (2014). Biodegradation of Sulfamethoxazole by *Phanerochaete chrysosporium*. *J. Mol. Liquids* 198, 169–172. doi:10.1016/j.molliq.2014.06.017
- Guo, X.-p., Liu, X., Niu, Z.-s., Lu, D.-p., Zhao, S., Sun, X.-l., et al. (2018). Seasonal and Spatial Distribution of Antibiotic Resistance Genes in the Sediments along the Yangtze Estuary, China. *Environ. Pollut.* 242, 576–584. doi:10.1016/j.envpol.2018.06.099
- Guo, X.-p., Zhao, S., Chen, Y.-r., Yang, J., Hou, L.-j., Liu, M., et al. (2020). Antibiotic Resistance Genes in Sediments of the Yangtze Estuary: From 2007 to 2019. *Sci. Total Environ.* 744, 140713. doi:10.1016/j.scitotenv.2020.140713
- Han, Q. F., Zhao, S., Zhang, X. R., Wang, X. L., Song, C., and Wang, S. G. (2020). Distribution, Combined Pollution and Risk Assessment of Antibiotics in Typical marine Aquaculture Farms Surrounding the Yellow Sea, North China. *Environ. Int.* 138, 105551. doi:10.1016/j.envint.2020.105551
- Hao, Q., Xu, X., Chen, H., Liu, S., Chen, J., Liu, S., et al. (2017). Residual Antibiotics in the Nansha Aquaculture Area of Guangzhou. *J. Trop. Oceanogr.* 36, 106–113. doi:10.11978/2016001
- Harrabi, M., Alexandrino, D. A. M., Aloulou, F., Elleuch, B., Liu, B., Jia, Z., et al. (2019). Biodegradation of Oxytetracycline and Enrofloxacin by Autochthonous Microbial Communities from Estuarine Sediments. *Sci. Total Environ.* 648, 962–972. doi:10.1016/j.scitotenv.2018.08.193
- He, S., Dong, D., Zhang, X., Sun, C., Wang, C., Hua, X., et al. (2018). Occurrence and Ecological Risk Assessment of 22 Emerging Contaminants in the Jilin Songhua River (Northeast China). *Environ. Sci. Pollut. Res.* 25, 24003–24012. doi:10.1007/s11356-018-2459-3
- He, X. T., Wang, Q., Nie, X. P., Yang, Y. T., and Cheng, Z. (2014). [Residues and Health Risk Assessment of Sulfonamides in Sediment and Fish from Typical marine Aquaculture Regions of Guangdong Province, China]. *Huan Jing Ke Xue* 35, 2728–2735.
- Hijosa-Valsero, M., Fink, G., Schlüsener, M. P., Sidrach-Cardona, R., Martín-Villacorta, J., Ternes, T., et al. (2011b). Removal of Antibiotics from Urban Wastewater by Constructed Wetland Optimization. *Chemosphere* 83, 713–719. doi:10.1016/j.chemosphere.2011.02.004
- Hijosa-Valsero, M., Sidrach-Cardona, R., Martín-Villacorta, J., Cruz Valsero-Blanco, M., Bayona, J. M., and Bécares, E. (2011a). Statistical Modelling of Organic Matter and Emerging Pollutants Removal in Constructed Wetlands. *Bioresour. Technology* 102, 4981–4988. doi:10.1016/j.biortech.2011.01.063
- Hofmann, U., and Schlosser, D. (2016). Biochemical and Physicochemical Processes Contributing to the Removal of Endocrine-Disrupting Chemicals and Pharmaceuticals by the Aquatic Ascomycete *Phoma* Sp. UHH 5-1-03. *Appl. Microbiol. Biotechnol.* 100, 2381–2399. doi:10.1007/s00253-015-7113-0
- Hu, Y., Yan, X., Shen, Y., Di, M., and Wang, J. (2019). Occurrence, Behavior and Risk Assessment of Estrogens in Surface Water and Sediments from Hanjiang River, Central China. *Ecotoxicology* 28, 143–153. doi:10.1007/s10646-018-2007-4
- Hu, Y., Yang, X., Li, J., Lv, N., Liu, F., Wu, J., et al. (2016). The Bacterial Mobile Resistome Transfer Network Connecting the Animal and Human Microbiomes. *Appl. Environ. Microbiol.* 82, 6672–6681. doi:10.1128/aem.01802-16
- Huang, X., Liu, C., Li, K., Su, J., Zhu, G., and Liu, L. (2015). Performance of Vertical Up-Flow Constructed Wetlands on Swine Wastewater Containing Tetracyclines and Tet Genes. *Water Res.* 70, 109–117. doi:10.1016/j.watres.2014.11.048
- Huddleston, J. R. (2014). Horizontal Gene Transfer in the Human Gastrointestinal Tract: Potential Spread of Antibiotic Resistance Genes. *Idr* 7, 167–176. doi:10.2147/idr.s48820
- Ioannou-Tofa, L., Raj, S., Prakash, H., and Fatta-Kassinos, D. (2019). Solar Photo-Fenton Oxidation for the Removal of Ampicillin, Total Cultivable and Resistant *E. coli* and Ecotoxicity from Secondary-Treated Wastewater Effluents. *Chem. Eng. J.* 355, 91–102. doi:10.1016/j.cej.2018.08.057
- Ji, X., Shen, Q., Liu, F., Ma, J., Xu, G., Wang, Y., et al. (2012). Antibiotic Resistance Gene Abundances Associated with Antibiotics and Heavy Metals in Animal Manures and Agricultural Soils Adjacent to Feedlots in Shanghai, China. *J. Hazard. Mater.* 235–236, 178–185. doi:10.1016/j.jhazmat.2012.07.040
- Ji, Y., Fan, Y., Liu, K., Kong, D., and Lu, J. (2015). Thermo Activated Persulfate Oxidation of Antibiotic Sulfamethoxazole and Structurally Related Compounds. *Water Res.* 87, 1–9. doi:10.1016/j.watres.2015.09.005
- Jia, Y., Khanal, S. K., Zhang, H., Chen, G.-H., and Lu, H. (2017). Sulfamethoxazole Degradation in Anaerobic Sulfate-Reducing Bacteria Sludge System. *Water Res.* 119, 12–20. doi:10.1016/j.watres.2017.04.040
- Johnson, T. A., Stedtfield, R. D., Wang, Q., Cole, J. R., Hashsham, S. A., Looft, T., et al. (2016). Clusters of Antibiotic Resistance Genes Enriched Together Stay Together in Swine Agriculture. *mBio* 7, e02214–02215. doi:10.1128/mbio.02214-15
- Kara, Fox. (2019). CNN. The World's Rivers Are Contaminated with Antibiotics, New Study shows[EB/OL]. Available at: <https://edition.cnn.com/2019/05/27/health/antibiotics-contaminate-worlds-rivers-intl-scli/index.html> (Accessed May 27, 2019).
- Kenyon, S., Pike, K., Jones, D., Brocklehurst, P., Marlow, N., Salt, A., et al. (2008). Childhood Outcomes after Prescription of Antibiotics to Pregnant Women with Spontaneous Preterm Labour: 7-year Follow-Up of the ORACLE II Trial. *The Lancet* 372, 1319–1327. doi:10.1016/s0140-6736(08)61203-9
- Kim, S.-C., and Carlson, K. (2007). Temporal and Spatial Trends in the Occurrence of Human and Veterinary Antibiotics in Aqueous and River Sediment Matrices. *Environ. Sci. Technol.* 41, 50–57. doi:10.1021/es060737+
- Koebnick, C., Tartof, S. Y., Sidell, M. A., Rozema, E., Chung, J., Chiu, V. Y., et al. (2019). Effect of In-Utero Antibiotic Exposure on Childhood Outcomes: Methods and Baseline Data of the Fetal Antibiotic Exposure (FAX) Cohort Study. *JMIR. Res. Protoc.* 8, e12065. doi:10.2196/12065
- Kumar, K., C. Gupta, S. S., Chander, Y., and Singh, A. K. (2005). “Antibiotic Use in Agriculture and its Impact on the Terrestrial Environment,” in *Advances in Agronomy* (Academic Press), 1–54. doi:10.1016/s0065-2113(05)87001-4

- Kümmerer, K. (2009). Antibiotics in the Aquatic Environment - A Review - Part I. *Chemosphere* 75, 417–434. doi:10.1016/j.chemosphere.2008.11.086
- Kümmerer, K. (2009). Antibiotics in the Aquatic Environment - A Review. Part I. *Chemosphere* 75, 347–354. doi:10.1016/j.chemosphere.2008.11.086
- Lanzky, P. F., and Halling-Sorensen, B. (1998). The Toxic Effect of the Antibiotic Metronidazole on Aquatic Organisms. *Chemosphere* 35, 2553–2561. doi:10.1016/S0045-6535(97)00324-X
- Le, T. X. H., Nguyen, T. V., Yacouba, Z. A., Zougrana, L., Avril, F., Petit, E., et al. (2016). Toxicity Removal Assessments Related to Degradation Pathways of Azo Dyes: Toward an Optimization of Electro-Fenton Treatment. *Chemosphere* 161, 308–318. doi:10.1016/j.chemosphere.2016.06.108
- Lee, S. S., and Carlson, K. (2006). Occurrence of Ionophore Antibiotics in Water and Sediments of a Mixed-Landscape Watershed. *Water Res.* 40, 2549–2560. doi:10.1016/j.watres.2006.04.036
- Li, D., Zeng, S., He, M., and Gu, A. Z. (2016). Water Disinfection Byproducts Induce Antibiotic Resistance-Role of Environmental Pollutants in Resistance Phenomena. *Environ. Sci. Technol.* 50, 3193–3201. doi:10.1021/acs.est.5b05113
- Li, F., Chen, L., Chen, W., Bao, Y., Zheng, Y., Huang, B., et al. (2020b). Antibiotics in Coastal Water and Sediments of the East China Sea: Distribution, Ecological Risk Assessment and Indicators Screening. *Mar. Pollut. Bull.* 151, 110810. doi:10.1016/j.marpolbul.2019.110810
- Li, P., Wu, Y., He, Y., Zhang, B., Huang, Y., Yuan, Q., et al. (2020a). Occurrence and Fate of Antibiotic Residues and Antibiotic Resistance Genes in a Reservoir with Ecological Purification Facilities for Drinking Water Sources. *Sci. Total Environ.* 707, 135276. doi:10.1016/j.scitotenv.2019.135276
- Li, S., Shi, W., Li, H., Xu, N., Zhang, R., Chen, X., et al. (2018). Antibiotics in Water and Sediments of Rivers and Coastal Area of Zhuhai City, Pearl River Estuary, south China. *Sci. Total Environ.* 636, 1009–1019. doi:10.1016/j.scitotenv.2018.04.358
- Li, W., Shi, Y., Gao, L., Liu, J., and Cai, Y. (2012b). Investigation of Antibiotics in Mollusks from Coastal Waters in the Bohai Sea of China. *Environ. Pollut.* 162, 56–62. doi:10.1016/j.envpol.2011.10.022
- Li, W., Shi, Y., Gao, L., Liu, J., and Cai, Y. (2012a). Occurrence of Antibiotics in Water, Sediments, Aquatic Plants, and Animals from Baiyangdian Lake in North China. *Chemosphere* 89, 1307–1315. doi:10.1016/j.chemosphere.2012.05.079
- Lian, L. (2016). *Distribution of Antibiotics in Surface and Core Sediments from Aquaculture*. Dalian, China: Areas Dalian University of Technology.
- Liang, D. H., and Hu, Y. (2021). Application of a Heavy Metal-Resistant *Achromobacter* Sp. for the Simultaneous Immobilization of Cadmium and Degradation of Sulfamethoxazole from Wastewater. *J. Hazard. Mater.* 402, 124032. doi:10.1016/j.jhazmat.2020.124032
- Liang, D. H., Hu, Y., Cheng, J., and Chen, Y. (2020). Simultaneous Sulfamethoxazole Biodegradation and Nitrogen Conversion in Low C/N Ratio Pharmaceutical Wastewater by *Achromobacter* Sp. JL9. *Sci. Total Environ.* 703, 135586. doi:10.1016/j.scitotenv.2019.135586
- Liang, S. (2019). *Distribution Characteristics and Risk Assessment of Antibiotics in Lancang and Yarlung Zangbo Rivers*. Beijing, China: China University of Geosciences.
- Liao, J., Wei, X. Q., Xiao, Y. Q., Li, Q. S., Fan, H. Y., Liu, X. J., et al. (2020). [Pollution Characteristics and Risk Assessment of Antibiotics in Lianhua Reservoir]. *Huan Jing Ke Xue* 41, 4081–4087. doi:10.13227/j.hj.kx.202002084
- Limbu, S. M., Zhou, L., Sun, S.-X., Zhang, M.-L., and Du, Z.-Y. (2018). Chronic Exposure to Low Environmental Concentrations and Legal Aquaculture Doses of Antibiotics Cause Systemic Adverse Effects in Nile tilapia and Provoke Differential Human Health Risk. *Environ. Int.* 115, 205–219. doi:10.1016/j.envint.2018.03.034
- Liu, J., Lu, G., Wang, Y., Yan, Z., Yang, X., Ding, J., et al. (2014). Bioconcentration, Metabolism, and Biomarker Responses in Freshwater Fish *Carassius auratus* Exposed to Roxithromycin. *Chemosphere* 99, 102–108. doi:10.1016/j.chemosphere.2013.10.036
- Liu, J., Lu, G., Yang, X., and Jin, S. (2012). Distribution, Accumulation and Ecotoxicological Effects of Antibiotics in Aquatic Environment. *Adm. Tech. Environ. Monit.* 24, 14–20.
- Liu, L., Liu, C., Zheng, J., Huang, X., Wang, Z., Liu, Y., et al. (2013). Elimination of Veterinary Antibiotics and Antibiotic Resistance Genes from Swine Wastewater in the Vertical Flow Constructed Wetlands. *Chemosphere* 91, 1088–1093. doi:10.1016/j.chemosphere.2013.01.007
- Liu, M., Zhou, Z., Liu, Y., Zhao, J., and Cai, Y. (2017). Distribution Characteristics of Antibiotics in Part of Pearl River. *Guangzhou Chem. Industry*.
- Liu, S., Zhang, L., Li, H., Chen, M., Chen, L., Wang, J., et al. (2020b). Occurrence, Distribution and Ecological Risk Assessment of Antibiotics in Sediments of Minjiang Estuary. *J. Oper. Oceanogr.* 39, 162–171. doi:10.3969/J.ISSN.2095-4972.2020.02.002
- Liu, T., Lun, J., Zheng, P., Feng, J., Meng, S., Peng, T., et al. (2020c). Diversity and Distribution of Antibiotics and Antibiotic Resistance Genes in Seven National Mangrove Nature Reserves, South China. *Int. Biodeterioration Biodegradation* 153, 105000. doi:10.1016/j.ibiod.2020.105000
- Liu, X., Guo, X., Liu, Y., Lu, S., Xi, B., Zhang, J., et al. (2019). A Review on Removing Antibiotics and Antibiotic Resistance Genes from Wastewater by Constructed Wetlands: Performance and Microbial Response. *Environ. Pollut.* 254, 112996. doi:10.1016/j.envpol.2019.112996
- Liu, X., Lu, S., Guo, W., Xi, B., and Wang, W. (2018). Antibiotics in the Aquatic Environments: A Review of Lakes, China. *Sci. Total Environ.* 627, 1195–1208. doi:10.1016/j.scitotenv.2018.01.271
- Liu, X., and Lu, S. (2018). Occurrence and Ecological Risk of Typical Antibiotics in Surface Water of the Datong Lake, China. *Environ. Sci.* 38, 320–329. doi:10.19674/j.cnki.issn1000-6923.2018.0038
- Liu, Y., Feng, M., Wang, B., Zhao, X., Guo, R., Bu, Y., et al. (2020a). Distribution and Potential Risk Assessment of Antibiotic Pollution in the Main Drinking Water Sources of Nanjing, China. *Environ. Sci. Pollut. Res.* 27, 21429–21441. doi:10.1007/s11356-020-08516-7
- Liu, Y., Li, Z., Feng, Y., Cheng, D., Hu, H., and Zhang, W. (2016). Research Progress in Microbial Degradation of Antibiotics. *J. Agro-environ. Sci.* 35, 212–224.
- Liyana, G. Y., and Manage, P. M. (2018). Removal of Ciprofloxacin (CIP) by Bacteria Isolated from Hospital Effluent Water and Identification of Degradation Pathways. *Ijmpd* 2, 37–47. doi:10.22216/ijmpd.2.3.1
- Llorca, M., Rodríguez-Mozaz, S., Coullero, O., Panigoni, K., de Gunzburg, J., Bayer, S., et al. (2015). Identification of New Transformation Products during Enzymatic Treatment of Tetracycline and Erythromycin Antibiotics at Laboratory Scale by an On-Line Turbulent Flow Liquid-Chromatography Coupled to a High Resolution Mass Spectrometer LTQ-Orbitrap. *Chemosphere* 119, 90–98. doi:10.1016/j.chemosphere.2014.05.072
- Loftin, K. A., Adams, C. D., Meyer, M. T., and Surampalli, R. (2008). Effects of Ionic Strength, Temperature, and pH on Degradation of Selected Antibiotics. *J. Environ. Qual.* 37, 378–386. doi:10.2134/jeq2007.0230
- Lü, L., Zhang, M. L., Wang, C. M., Lin, H. R., and Yu, X. (2015). [Effect of Three Typical Disinfection Byproducts on Bacterial Antibiotic Resistance]. *Huan Jing Ke Xue* 36, 2525–2531. doi:10.13227/j.hj.kx.2015.07.027
- Lv, L., Yu, X., Xu, Q., and Ye, C. (2015). Induction of Bacterial Antibiotic Resistance by Mutagenic Halogenated Nitrogenous Disinfection Byproducts. *Environ. Pollut.* 205, 291–298. doi:10.1016/j.envpol.2015.06.026
- Lyu, K., Liu, X., Deng, C., Zheng, K., Li, L., Shi, J., et al. (2019). Determination of 14 Antibiotics in Water and Sediment by SPE-RRLC-MS/MS. *Environ. Chem.* 38, 2415–2424. doi:10.7524/j.issn.0254-6108.2018122904
- Madan, J. C., Salari, R. C., Saxena, D., Davidson, L., O'Toole, G. A., Moore, J. H., et al. (2012). Gut Microbial Colonisation in Premature Neonates Predicts Neonatal Sepsis. *Arch. Dis. Child. Fetal Neonatal. Ed. Heart* 2012 97 (6), F456–F462. doi:10.1136/fetalneonatal-2011-301373
- Maia, A. S., Tiritan, M. E., and Castro, P. M. L. (2018). Enantioselective Degradation of Ofloxacin and Levofloxacin by the Bacterial Strains *Labrys portucalensis* F11 and *Rhodococcus* Sp. FP1. *Ecotoxicology Environ. Saf.* 155, 144–151. doi:10.1016/j.ecoenv.2018.02.067
- Mangalgi, K. P., and Blaney, L. (2017). Elucidating the Stimulatory and Inhibitory Effects of Dissolved Organic Matter from Poultry Litter on Photodegradation of Antibiotics. *Environ. Sci. Technol.* 51, 12310–12320. doi:10.1021/acs.est.7b03482
- Mao, F., Liu, X., Wu, K., Zhou, C., and Si, Y. (2018). Biodegradation of Sulfonamides by *Shewanella oneidensis* MR-1 and *Shewanella* Sp. Strain MR-4. *Biodegradation* 29, 129–140. doi:10.1007/s10532-017-9818-5
- Marcelo, C., Susana, R., and Augusto, S. (2020). [Use (and abuse) of antibiotics in perinatal medicine]. *Anales de pediatria*. Barcelona, Spain.

- Martins, M., Sanches, S., and Pereira, I. A. C. (2018). Anaerobic Biodegradation of Pharmaceutical Compounds: New Insights into the Pharmaceutical-Degrading Bacteria. *J. Hazard. Mater.* 357, 289–297. doi:10.1016/j.jhazmat.2018.06.001
- Matamoros, V., and Bayona, J. M. (2006). Elimination of Pharmaceuticals and Personal Care Products in Subsurface Flow Constructed Wetlands. *Environ. Sci. Technol.* 40, 5811–5816. doi:10.1021/es0607741
- McInnes, R. S., Mccallum, G. E., Lamberte, L. E., and Van Schaik, W. (2020). Horizontal Transfer of Antibiotic Resistance Genes in the Human Gut Microbiome. *Curr. Opin. Microbiol.* 53, 35–43. doi:10.1016/j.mib.2020.02.002
- Meng, Y., Feng, Y., Li, X., Liu, Y., and Li, Z. (2018). Isolation of an Oxytetracycline-Degrading Bacterial Strain and its Biodegradation Characteristics. *Plant Nutr. Fert. Sci.* 24, 720–727. doi:10.11674/zwfy.17161
- Metsälä, J., Lundqvist, A., Virta, L. J., Kaila, M., Gissler, M., and Virtanen, S. M. (2015). Prenatal and post-natal Exposure to Antibiotics and Risk of Asthma in Childhood. *Clin. Exp. Allergy* 45, 137–145. doi:10.1111/cea.12356
- Mette, N., Vera, E., Beck, N. R., Sigmund, B. L., Toft, S. H., and Ratner, A. J. (2012). Maternal Use of Antibiotics, Hospitalisation for Infection during Pregnancy, and Risk of Childhood Epilepsy: A Population-Based Cohort Study. *Plos One* 7, e30850.
- Milliken, S., Allen, R. M., and Lamont, R. F. (2019). The Role of Antimicrobial Treatment during Pregnancy on the Neonatal Gut Microbiome and the Development of Atopy, Asthma, Allergy and Obesity in Childhood. *Expert Opin. Drug Saf.* 18, 173–185. doi:10.1080/14740338.2019.1579795
- Möhle, L., Mattei, D., Heimesaat, M. M., Bereswill, S., Fischer, A., Alutis, M., et al. (2016). Ly6Chi Monocytes Provide a Link between Antibiotic-Induced Changes in Gut Microbiota and Adult Hippocampal Neurogenesis. *Cel Rep.* 15, 1945–1956. doi:10.1016/j.celrep.2016.04.074
- Mosedale, M., Wu, H., Kurtz, C. L., Schmidt, S. P., Adkins, K., and Harrill, A. H. (2014). Dysregulation of Protein Degradation Pathways May Mediate the Liver Injury and Phospholipidosis Associated with a Cationic Amphiphilic Antibiotic Drug. *Toxicol. Appl. Pharmacol.* 280, 21–29. doi:10.1016/j.taap.2014.06.013
- Mountassir, E. M., Benazziz, L., Rafqah, S., and Lakraimi, M. (2020). Development of a New Recyclable Nanocomposite LDH-TiO₂ for the Degradation of Antibiotic Sulfamethoxazole under UVA Radiation: an Approach towards Sunlight. *J. Photoch. Photobio. A.* 396, 112530. doi:10.1016/j.jphotochem.2020.112530
- Mulla, S. I., Hu, A., Sun, Q., Li, J., Suanon, F., Ashfaq, M., et al. (2018). Biodegradation of Sulfamethoxazole in Bacteria from Three Different Origins. *J. Environ. Manage.* 206, 93–102. doi:10.1016/j.jenvman.2017.10.029
- Mushtaq, K., Saeed, M., Gul, W., Munir, M., Firdous, A., Yousaf, T., et al. (2020). Synthesis and Characterization of TiO₂ via Sol-Gel Method for Efficient Photocatalytic Degradation of Antibiotic Ofloxacin. *Inorg. Nano-Metal Chem.* 50, 580–586. doi:10.1080/24701556.2020.1722695
- Nassar, R., Rifai, A., Trivella, A., Mazellier, P., Mokh, S., and Al-Iskandarani, M. (2018). Aqueous Chlorination of Sulfamethazine and Sulfamethoxyypyridazine: Kinetics and Transformation Products Identification. *J. Mass. Spectrom.* 53, 614–623. doi:10.1002/jms.4191
- Neu, J., and Walker, W. A. (2011). Necrotizing Enterocolitis. *N. Engl. J. Med.* 364, 255–264. doi:10.1056/nejmra1005408
- Nguyen, L. N., Nghiem, L. D., and Oh, S. (2018). Aerobic Biotransformation of the Antibiotic Ciprofloxacin by Bradyrhizobium Sp. Isolated from Activated Sludge. *Chemosphere* 211, 600–607. doi:10.1016/j.chemosphere.2018.08.004
- Pan, L.-J., Li, J., Li, C.-x., Tang, X.-d., Yu, G.-W., and Wang, Y. (2018). Study of Ciprofloxacin Biodegradation by a Thermus Sp. Isolated from Pharmaceutical Sludge. *J. Hazard. Mater.* 343, 59–67. doi:10.1016/j.jhazmat.2017.09.009
- Park, N., Vanderford, B. J., Snyder, S. A., Sarp, S., Kim, S. D., and Cho, J. (2009). Effective Controls of Micropollutants Included in Wastewater Effluent Using Constructed Wetlands under Anoxic Condition Using Constructed Wetlands under Anoxic Condition. *Ecol. Eng.* 35, 418–423. doi:10.1016/j.ecoleng.2008.10.004
- Park, Y. J., Chang, J., Lee, G., Son, J. S., and Park, S. M. (2020). Association of Class Number, Cumulative Exposure, and Earlier Initiation of Antibiotics during the First Two-Years of Life with Subsequent Childhood Obesity. *Metabolism* 112, 154348. doi:10.1016/j.metabol.2020.154348
- Peng, Y., Zhang, Y., Huang, H., and Zhong, C. (2018). Flexibility Induced High-Performance MOF-Based Adsorbent for Nitroimidazole Antibiotics Capture. *Chem. Eng. J.* 333, 678–685. doi:10.1016/j.ccej.2017.09.138
- Pérez, S., and Barceló, D. (2008). First Evidence for Occurrence of Hydroxylated Human Metabolites of Diclofenac and Aceclofenac in Wastewater Using QqLIT-MS and QqTOF-MS. *Anal. Chem.* 80, 8135–8145. doi:10.1021/ac801167w
- Pérez-Grisales, M. S., Castrillón-Tobón, M., Copete-Pertuz, L. S., Plácido, J., and Mora-Martínez, A. L. (2019). Biotransformation of the Antibiotic Agent Cephadroxy and the Synthetic Dye Reactive Black 5 by Leptosphaerulina Sp. Immobilised on Luffa (Luffa Cylindrica) Sponge. *Biocatal. Agric. Biotechnol.* 18, 101051. doi:10.1016/j.bcab.2019.101051
- Pronovost, G. N., and Hsiao, E. Y. (2019). Perinatal Interactions between the Microbiome, Immunity, and Neurodevelopment. *Immunity* 50, 18–36. doi:10.1016/j.immuni.2018.11.016
- Qian, Z., Tang, S., Liang, Y., Wei, S., Luo, F., and Chen, S. (2019). Simultaneous Determination of Sulfonamides, Quinolones and Macrolides Antibiotics Residues in Sediment from Aquaculture Environment by QuEChERS-HPLC-MS/MS. *J. Chin. Mass. Spectrom. Soc.* 40, 356–368. doi:10.7538/zpxb.2018.0128
- Qianqian, W. (2016). *Pollution Levels of Antibiotics from Aquatic Environment in Alashankou Region of Xinjiang and Surrounding Area*. Shihezi, China: Shihezi University. doi:10.1109/ccdc.2016.7531705
- Qing, C., Shang, C., Zhou, Y., Lin, Y., Shao, J., and Chen, A. (2018). Study on the Biodegradation of Tetracycline Wastewater by *Phanerochaete Chrysosporium*. *Environ. Pollut. Control.* 40, 1023–1026+1067. doi:10.15985/j.cnki.1001-3865.2018.09.014
- Radjenovic, J., Petrovic, M., and Barcelo, D. (2009). Fate and Distribution of Pharmaceuticals in Wastewater and Sewage Sludge of the Conventional Activated Sludge (CAS) and Advanced Membrane Bioreactor (MBR) Treatment. *Water Res.* 43, 831–841. doi:10.1016/j.watres.2008.11.043
- Radke, M., Lauwigi, C., Heinkele, G., Mürdter, T. E., and Letzel, M. (2009). Fate of the Antibiotic Sulfamethoxazole and its Two Major Human Metabolites in a Water Sediment Test. *Environ. Sci. Technol.* 43, 3135–3141. doi:10.1021/es900300u
- Ramirez, A. J., Mottaleb, M. A., Brooks, B. W., and Chambliss, C. K. (2007). Analysis of Pharmaceuticals in Fish Using Liquid Chromatography-Tandem Mass Spectrometry. *Anal. Chem.* 79, 3155–3163. doi:10.1021/ac062215i
- Reis, P. J. M., Homem, V., Alves, A., Vilar, V. J. P., Manaia, C. M., and Nunes, O. C. (2018). Insights on Sulfamethoxazole Bio-Transformation by Environmental Proteobacteria Isolates. *J. Hazard. Mater.* 358, 310–318. doi:10.1016/j.jhazmat.2018.07.012
- Rico, A., Phu, T. M., Satapornvanit, K., Min, J., Shahabuddin, A. M., Henriksson, P. J. G., et al. (2013). Use of Veterinary Medicines, Feed Additives and Probiotics in Four Major Internationally Traded Aquaculture Species Farmed in Asia. *Aquaculture* 412–413, 231–243. doi:10.1016/j.aquaculture.2013.07.028
- Russell, J. N., and Yost, C. K. (2021). Alternative, Environmentally Conscious Approaches for Removing Antibiotics from Wastewater Treatment Systems. *Chemosphere* 263, 128177. doi:10.1016/j.chemosphere.2020.128177128177
- Scott, F. I., Horton, D. B., Mamtani, R., Haynes, K., Goldberg, D. S., Lee, D. Y., et al. (2016). Administration of Antibiotics to Children before Age 2 Years Increases Risk for Childhood Obesity. *Gastroenterology* 151, 120–129. doi:10.1053/j.gastro.2016.03.006
- Shakerian, F., Zhao, J., and Li, S.-P. (2020). Recent Development in the Application of Immobilized Oxidative Enzymes for Bioremediation of Hazardous Micropollutants - A Review. *Chemosphere* 239, 124716. doi:10.1016/j.chemosphere.2019.124716
- Shao, B., Liu, Z., Zeng, G., Liu, Y., Yang, X., Zhou, C., et al. (2019). Immobilization of Laccase on Hollow Mesoporous Carbon Nanospheres: Noteworthy Immobilization, Excellent Stability and Efficacious for Antibiotic Contaminants Removal. *J. Hazard. Mater.* 362, 318–326. doi:10.1016/j.jhazmat.2018.08.069
- Shao, S., Hu, Y., Cheng, C., Cheng, J., and Chen, Y. (2018a). Simultaneous Degradation of Tetracycline and Denitrification by a Novel Bacterium, *Klebsiella* Sp. SQY5. *Chemosphere* 209, 35–43. doi:10.1016/j.chemosphere.2018.06.093
- Shao, S., Hu, Y., Cheng, J., and Chen, Y. (2018b). Degradation of Oxytetracycline (OTC) and Nitrogen Conversion Characteristics Using a Novel Strain. *Chem. Eng. J.* 354, 758–766. doi:10.1016/j.ccej.2018.08.032
- Shao, Z., Li, H., Li, X., Xu, Y., and Zheng, X. (2020). The Occurrence and Risk Management of Antibiotics and Antibiotic Resistant Genes in Rural Solid Waste. *Asian J. Org. Chem.* 15, 112–122.

- Shi, M., Zhu, X., and Tang, W. (2015). Progress in Research of the Environmental Effects of Antibiotic Resistance Genes. *Environ. Prot. Sci.* 41, 123–128. doi:10.16803/j.cnki.issn.1004-6216.2015.06.027
- Simón-Herrero, C., Naghdi, M., Taheran, M., Kaur Brar, S., Romero, A., Valverde, J. L., et al. (2019). Immobilized Laccase on Polyimide Aerogels for Removal of Carbamazepine. *J. Hazard. Mater.* 376, 83–90. doi:10.1016/j.jhazmat.2019.05.032
- Singh, S. K., Khajuria, R., and Kaur, L. (2017). Biodegradation of Ciprofloxacin by white Rot Fungus *Pleurotus Ostreatus*. *3 Biotech.* 7, 7. doi:10.1007/s13205-017-0684-y
- Siswanto, S., Arozal, W., Juniantito, V., Grace, A., Agustini, F. D., and Nafrialdi, N. (2016). The Effect of Mangiferin against Brain Damage Caused by Oxidative Stress and Inflammation Induced by Doxorubicin. *HAYATI J. Biosciences* 23, 51–55. doi:10.1016/j.hjb.2016.02.001
- Sobhani, I., Bergsten, E., Couffin, S., Amiot, A., Nebbad, B., Barau, C., et al. (2019). Colorectal Cancer-Associated Microbiota Contributes to Oncogenic Epigenetic Signatures. *Proc. Natl. Acad. Sci. USA* 116, 24285–24295. doi:10.1073/pnas.1912129116
- Sun, Q., Wang, Z., Dong, J., Chen, C., Chen, Q., Liu, J., et al. (2018). Spatialtemporal Distribution and Risk Evaluation of Four Typical Antibiotics in River Networks of Taihu Lake Basin. *Acta Scientiae Circumstantiae.* 38, 4400–4410. doi:10.13671/j.hjkxxb.2018.0212
- Susarla, S., Medina, V. F., and McCutcheon, S. C. (2002). Phytoremediation: An Ecological Solution to Organic Chemical Contamination. *Ecol. Eng.* 18, 647–658. doi:10.1016/S0925-8574(02)00026-5
- Tadeusz, P., Rafał, K., Alicja, B., and Zbigniew, S. (2019). [The Growing Resistance of Bacterial Strains to Antibiotics]. *Polski Merkuriusz Lekarski : Organ. Polskiego Towarzystwa Lekarskiego* 47 (279), 106–110.
- Tang, J., Shi, T., Wu, X., Cao, H., Li, X., Hua, R., et al. (2015). The Occurrence and Distribution of Antibiotics in Lake Chaohu, China: Seasonal Variation, Potential Source and Risk Assessment. *Chemosphere* 122, 154–161. doi:10.1016/j.chemosphere.2014.11.032
- Tang, J., Wang, S., Tai, Y., Tam, N. F., Su, L., Shi, Y., et al. (2020). Evaluation of Factors Influencing Annual Occurrence, Bioaccumulation, and Biomagnification of Antibiotics in Planktonic Food Webs of a Large Subtropical River in South China. *Water Res.* 170, 115302. doi:10.1016/j.watres.2019.115302
- Terzic, S., Udikovic-Kolic, N., Jurina, T., Krizman-Matasic, I., Senta, I., Mihaljevic, I., et al. (2018). Biotransformation of Macrolide Antibiotics Using Enriched Activated Sludge Culture: Kinetics, Transformation Routes and Ecotoxicological Evaluation. *J. Hazard. Mater.* 349, 143–152. doi:10.1016/j.jhazmat.2018.01.055
- Touahar, I. E., Haroune, L., Ba, S., Bellenger, J.-P., and Cabana, H. (2014). Characterization of Combined Cross-Linked Enzyme Aggregates from Laccase, Versatile Peroxidase and Glucose Oxidase, and Their Utilization for the Elimination of Pharmaceuticals. *Sci. Total Environ.* 481, 90–99. doi:10.1016/j.scitotenv.2014.01.132
- Tunç, S., Duman, O., and Gürkan, T. (2013). Monitoring the Decolorization of Acid Orange 8 and Acid Red 44 from Aqueous Solution Using Fenton's Reagents by Online Spectrophotometric Method: Effect of Operation Parameters and Kinetic Study. *Ind. Eng. Chem. Res.* 52, 1414–1425. doi:10.1021/ie302126c
- Tunç, S., Gürkan, T., and Duman, O. (2012). On-Line Spectrophotometric Method for the Determination of Optimum Operation Parameters on the Decolorization of Acid Red 66 and Direct Blue 71 from Aqueous Solution by Fenton Process. *Chem. Eng. J.* 181–182, 431–442. doi:10.1016/j.cej.2011.11.109
- Wang, D., and Wang, Q. (2020). Analysis on the Distribution of Antibiotics Pollution in the Water Environment of Weihe River Area in Huaihe River Basin. *Environ. Sci. Technol.* 45, 63–66.
- Wang, G., Zhou, S., Han, X., Zhang, L., Ding, S., Li, Y., et al. (2020b). Occurrence, Distribution, and Source Track of Antibiotics and Antibiotic Resistance Genes in the Main Rivers of Chongqing City, Southwest China. *J. Hazard. Mater.* 389, 122110. doi:10.1016/j.jhazmat.2020.122110
- Wang, J. (2020a). Removal of Pharmaceuticals and Personal Care Products (PPCPs) from Eastwater: a Review. *J. Sichuan Norm. Univ. Nat. Sci.* 43, 143–172.
- Wang, M., and Helbling, D. E. (2016). A Non-target Approach to Identify Disinfection Byproducts of Structurally Similar Sulfonamide Antibiotics. *Water Res.* 102, 241–251. doi:10.1016/j.watres.2016.06.042
- Wang, Q., Zhu, P., Xia, Z., Wang, Z., Zeng, Y., and Hou, Y. (2018b). Screening and Degradation Properties of Three Kinds of Agricultural Antibiotics Degrading Fungi. *J. Agric. Resour. Environ.* 35, 533–539. doi:10.13254/j.jare.2018.0069
- Wang, R., QiuQian, L., Li, G., Zong, Y., Tang, J., and Xu, Y. (2018d). Distribution Characteristics and Ecological Risk Assessment of Selected Antibiotics in Moon Lake, Ningbo City. *J. Lake Sci.* 30, 1616–1624. doi:10.18307/2018.0613
- Wang, S., Hu, Y., and Wang, J. (2018a). Biodegradation of Typical Pharmaceutical Compounds by a Novel Strain *Acinetobacter* Sp. *J. Environ. Manage.* 217, 240–246. doi:10.1016/j.jenvman.2018.03.096
- Wang, S., and Wang, J. (2018). Biodegradation and Metabolic Pathway of Sulfamethoxazole by a Novel Strain *Acinetobacter* Sp. *Appl. Microbiol. Biotechnol.* 102, 425–432. doi:10.1007/s00253-017-8562-4
- Wang, T., Hu, X., Liang, S., Li, W., Wu, X., Wang, L., et al. (2015). *Lactobacillus Fermentum* NS9 Restores the Antibiotic Induced Physiological and Psychological Abnormalities in Rats. *Beneficial Microbes* 6, 707–717. doi:10.3920/bm2014.0177
- Wang, W., Zhang, W., Liang, H., and Gao, D. (2018c). Seasonal Distribution Characteristics and Health Risk Assessment of Typical Antibiotics in the Harbin Section of the Songhua River basin. *Environ. Technology* 40, 2726–2737. doi:10.1080/09593330.2018.1449902
- Wang, Y. (2020b). *Distribution Characteristics of Typical Antibiotics, Antibiotic Resistance Genes and Microbial Community in Ebinur Lake Basin*. Ji'nan, China: Shandong Normal University.
- Wang, Y., Huang, H., Peng, J., Xie, S., Yang, H., Guo, F., et al. (2020a). Occurrence and Distribution of Typical Antibiotics in the Aquatic Environment of the Wetland Karst Plateau in Guizhou. *Environ. Chem.* 39, 975–986. doi:10.7524/j.issn.0254-6108.2019090103
- Wang, Y., Jia, H., Zhang, H., Wang, J., and Liu, W. (2017a). Performance of a Novel Recycling Magnetic Flocculation Membrane Filtration Process for Tetracycline-Polluted Surface Water Treatment. *Water Sci. Technol.* 76, 490–500. doi:10.2166/wst.2017.218
- Wang, Y., Peng, J., Huang, H., Tan, H., Zhang, A., Yang, H., et al. (2018e). Distribution Characteristics of Typical Antibiotics in Urban Rivers of Guiyang City. *Environ. Chem.* 37, 2039–2048.
- Wang, Z., Du, Y., Yang, C., Liu, X., Zhang, J., Li, E., et al. (2017b). Occurrence and Ecological hazard Assessment of Selected Antibiotics in the Surface Waters in and Around Lake Honghu, China. *Sci. Total Environ.* 609, 1423–1432. doi:10.1016/j.scitotenv.2017.08.009
- Wang, Z., Lei, Y., Xiao, J., Luo, Z., Zhong, H., Guo, Z., et al. (2019). Residue Status of Antibiotics in Aquaculture Ponds of Main tilapia Aquaculture Areas in Guangxi. *J. South. Agric.* 50, 891–897. doi:10.3969/j.issn.2095-1191.2019.04.29
- Wei, R., He, T., Zhang, S., Zhu, L., Shang, B., Li, Z., et al. (2019). Occurrence of Seventeen Veterinary Antibiotics and Resistant Bacterias in Manure-Fertilized Vegetable Farm Soil in Four Provinces of China. *Chemosphere* 215, 234–240. doi:10.1016/j.chemosphere.2018.09.152
- Wen, X., Jia, Y., and Li, J. (2009). Degradation of Tetracycline and Oxytetracycline by Crude Lignin Peroxidase Prepared from *Phanerochaete Chrysosporium* - A white Rot Fungus. *Chemosphere* 75, 1003–1007. doi:10.1016/j.chemosphere.2009.01.052
- Weng, S.-S., Ku, K.-L., and Lai, H.-T. (2012). The Implication of Mediators for Enhancement of Laccase Oxidation of Sulfonamide Antibiotics. *Bioresour. Technology* 113, 259–264. doi:10.1016/j.biortech.2011.12.111
- Weng, X., Owens, G., and Chen, Z. (2020). Synergetic Adsorption and Fenton-like Oxidation for Simultaneous Removal of Ofloxacin and Enrofloxacin Using green Synthesized Fe NPs. *Chem. Eng. J.* 382, 122871. doi:10.1016/j.cej.2019.122871
- Winek, K., Engel, O., Koduah, P., Heimesaat, M. M., Fischer, A., Bereswill, S., et al. (2016). Depletion of Cultivable Gut Microbiota by Broad-Spectrum Antibiotic Pretreatment Worsens Outcome after Murine Stroke. *Stroke* 47, 1354–1363. doi:10.1161/strokeaha.115.011800
- Wu, X., Wu, X., Li, J., Shen, L., Yu, R., and Zeng, W. (2018). Isolation and Degradation Characteristics of a Efficient Tetracyclinedegrading Strain. *Biotechnol. Bull.* 34, 172–178. doi:10.13560/j.cnki.biotech.bull.1985.2017-0723
- Wu, X. Y., Zou, H., Zhu, R., and Wang, J. G. (2016). [Occurrence, Distribution and Ecological Risk of Antibiotics in Surface Water of the Gonghu Bay, Taihu Lake]. *Huan Jing Ke Xue* 37, 4596–4604. doi:10.13227/j.hjkk.201603005
- Xian, Q., Hu, L., Chen, H., Chang, Z., and Zou, H. (2010). Removal of Nutrients and Veterinary Antibiotics from Swine Wastewater by a Constructed

- Macrophyte Floating Bed System. *J. Environ. Manage.* 91, 2657–2661. doi:10.1016/j.jenvman.2010.07.036
- Xiao, X., Wu, Y., Ding, H., Wan, L., Yang, W., and Zhang, W. (2019). Pollution Characteristics of Antibiotics and Antibiotic Resistance Genes in Urban Lakes of Wuhan. *Environ. Sci. Technol.* 42, 9–16. doi:10.19672/j.cnki.1003-6504.2019.03.002
- Xie, C., Yang, S.-t., Wei, Q., Jiang, X., Wang, Z., and Wu, X. (2019). Antibiotic Pollution Characteristics and Risk Assessment of Xinghu Lake in Zhaoqing. *J. Environ. Health* 36, 427–431. doi:10.16241/j.cnki.1001-5914.2019.05.012
- Xie, Q., Chen, Y., Wan, J., Wang, Y., and Yan, Z. (2020). Occurrence, Distribution and Risk Assessment of Antibiotics in Drinking Water Source in Dongguan. *Acta Scientiae Circumstantiae* 40, 166–178. doi:10.13671/j.hjkkxb.2019.0334
- Xingxing, L., Jianguo, B., Yifei, L., Ying, L., Hui, G., and Jin, Z. (2016). Degradation Mechanism of Tetracycline by Lignin Peroxidase. *Saf. Environ. Eng.* 23, 61–68. doi:10.13578/j.cnki.issn.1671-1556.2016.05.01010.31723/2524-0447-2016-23-193-204
- Xu, B., Luo, Y., Zhou, Q., and Mao, D. (2010). Sources, Dissemination, and Ecological Risk of Antibiotic Resistances Genes (ARGs) in the Environment. *Environ. Chem.* 29, 169–178.
- Xu, L., Sun, B., Sheng, P., Shi, Q., and Luo, Y. (2019). Pollution Characteristics of Antibacterial Drugs in Typical Aquaculture Ponds in Huzhou Area. *Jiangsu Agric. Sci.* 47, 210–214. doi:10.15889/j.issn.1002-1302.2019.11.047
- Xu, L., Ye, X., Hao, G., Sheng, P., Zhou, D., Sun, B., et al. (2020). Typical Antibiotic Pollution Characteristics and Ecological Risk Assessment of Surface Water in Tiaoxi River. *Mod. Agr. Sci. Tech.* 180, 183+187.
- Xu, Z., Li, T., Bi, J., and Wang, C. (2018). Spatiotemporal Heterogeneity of Antibiotic Pollution and Ecological Risk Assessment in Taihu Lake Basin, China. *Sci. Total Environ.* 643, 12–20. doi:10.1016/j.scitotenv.2018.06.175
- Xuan, L., Huimin, Z., Hua, W., Lu, L., Shihui, W., and Qi, S. (2020). Impacts of Heavy Metals and Environmental Factors Assisted Antibiotics on Antibiotic Resistance Genes in Sediments in Dalian Typical Intertidal Mudflat Culture Areas. *J. Dalian Ocean Univ.* 35, 229–238. doi:10.16535/j.cnki.dlhyxb.2020-012
- Yamaguchi, K., Beligni, M. V., Prieto, S., Haynes, P. A., McDonald, W. H., Yates, J. R., et al. (2003). Proteomic Characterization of the Chlamydomonas Reinhardtii Chloroplast Ribosome. *J. Biol. Chem.* 278, 33774–33785. doi:10.1074/jbc.M301934200
- Yamaguchi, K., and Subramanian, A. R. (2003). Proteomic Identification of All Plastid-specific Ribosomal Proteins in Higher Plant Chloroplast 30S Ribosomal Subunit. PRSP-2 (U1A-type Domains), PRSP-3alpha/beta (Ycf65 Homologue) and PRSP-4 (Thx Homologue). *Eur. J. Biochem.* 270, 190–205. doi:10.1046/j.1432-1033.2003.03359.x
- Yan, R. (2019). *Occurrence Characteristics and Risk Assessment of Antibiotics and Other Drugs in Shanghai Livestock Farms*. Shanghai, China: East China Normal University.
- Yan, X. (2018). *Distribution, Sources and Risk Evaluation of Typical Antibiotics in Xiaoqing River Basin*. Ji'nan, China: Shandong Normal University.
- Yang, J.-F., Ying, G.-G., Zhao, J.-L., Tao, R., Su, H.-C., and Chen, F. (2010). Simultaneous Determination of Four Classes of Antibiotics in Sediments of the Pearl Rivers Using RRLC-MS/MS. *Sci. Total Environ.* 408, 3424–3432. doi:10.1016/j.scitotenv.2010.03.049
- Yang, X.-L., Xu, J.-Y., Song, H.-L., Wang, X., and Li, T. (2020). Enhanced Removal of Antibiotics in Wastewater by Membrane Bioreactor with Addition of rice Straw. *Int. Biodeterioration Biodegradation* 148, 104868. doi:10.1016/j.ibiod.2019.104868
- Yang, Y. (2018). *Concentration Levels and Distribution Characteristics of Various Antibiotics in Kaidu River and Kongque River in Bazhou Area*. Shihezi, China: Xinjiang Shihezi University.
- Yin, F., Ji, C., Dong, H., Tao, X., and Chen, Y. (2016). Research Progress on Effect of Antibiotic on Anaerobic Digestion Treatment in Animal Manure. *J. Agr. Sci. Tech-iran* 18, 171–177. doi:10.13304/j.nykjdb.2015.702
- Yin, F., Lin, S., Zhou, X., Dong, H., and Zhan, Y. (2021). Fate of Antibiotics during Membrane Separation Followed by Physical-Chemical Treatment Processes. *Sci. Total Environ.* 759, 143520. doi:10.1016/j.scitotenv.2020.143520
- Yoshizaki, S., and Tomida, T. (2000). Principle and Process of Heavy Metal Removal from Sewage Sludge. *Environ. Sci. Technol.* 34, 1572–1575. doi:10.1021/es990979s
- Yu, N., Fang, H., Hu, J., Wang, Z., Ding, C., Yuan, H., et al. (2020). Contamination Characteristics and Ecological Risk Assessment of Antibiotics in Four Typical *Procambarus clarkii* Aquaculture Environments in Jiangsu Province, China. *J. Environ. Sci. (China)* 39, 386–393. doi:10.11654/jaes.2019-0983
- Yuan, J., Ni, M., Liu, M., Zheng, Y., and Gu, Z. (2019). Occurrence of Antibiotics and Antibiotic Resistance Genes in a Typical Estuary Aquaculture Region of Hangzhou Bay, China. *Mar. Pollut. Bull.* 138, 376–384. doi:10.1016/j.marpolbul.2018.11.037
- Zdarta, J., Jankowska, K., Bachosz, K., Kijńska-Gawrońska, E., Zgola-Grześkowiak, A., Kaczorek, E., et al. (2020). A Promising Laccase Immobilization Using Electrospun Materials for Biocatalytic Degradation of Tetracycline: Effect of Process Conditions and Catalytic Pathways. *Catal. Today* 348, 127–136. doi:10.1016/j.cattod.2019.08.042
- Zeng, J., Pan, Y., Yang, J., Hou, M., Zeng, Z., and Xiong, W. (2019). Metagenomic Insights into the Distribution of Antibiotic Resistome between the Gut-Associated Environments and the Pristine Environments. *Environ. Int.* 126, 346–354. doi:10.1016/j.envint.2019.02.052
- Zhang, C., Feng, Y., Liu, Y., Cheng, D., Zheng, Y., and Li, Z. (2018a). The Degradation of Typical Antibiotics and Their Effects on Soil Bacterial Diversity in Spinach Soil. *Chin. Agric. Sci.* 51, 3736–3749. doi:10.3864/j.issn.0578-1752.2018.19.011
- Zhang, C., You, S., Zhang, J., Qi, W., Su, R., and He, Z. (2020a). An Effective In-Situ Method for Laccase Immobilization: Excellent Activity, Effective Antibiotic Removal Rate and Low Potential Ecological Risk for Degradation Products. *Bioresour. Technology* 308, 123271. doi:10.1016/j.biortech.2020.123271
- Zhang, H., Du, M., Jiang, H., Zhang, D., Lin, L., Ye, H., et al. (2014). Occurrence, Seasonal Variation and Removal Efficiency of Antibiotics and Their Metabolites in Wastewater Treatment Plants, Jiulongjiang River Basin, South China. *Environ. Sci. Process. Impacts* 17, 225–234. doi:10.1039/C4EM00457D
- Zhang, H., Song, S., Jia, Y., Wu, D., and Lu, H. (2019b). Stress-responses of Activated Sludge and Anaerobic Sulfate-Reducing Bacteria Sludge under Long-Term Ciprofloxacin Exposure. *Water Res.* 164, 114964. doi:10.1016/j.watres.2019.114964
- Zhang, J., Peng, X., and Jia, X. (2019c). Isolation and Characterization of Highly Efficient Sulfamethazine-Degrading Bacterium Strain J2. *Acta Scientiae Circumstantiae* 39, 2919–2927. doi:10.13671/j.hjkkxb.2019.0096
- Zhang, N., Li, M., and Liu, X. (2018b). Distribution and Transformation of Antibiotic Resistance Genes in Soil. *China Environ. Sci.* 38, 2609–2617. doi:10.19674/j.cnki.issn1000-6923.20180521.001
- Zhang, R., Pei, J., Zhang, R., Wang, S., Zeng, W., Huang, D., et al. (2018c). Occurrence and Distribution of Antibiotics in Mariculture Farms, Estuaries and the Coast of the Beibu Gulf, China: Bioconcentration and Diet Safety of Seafood. *Ecotoxicology Environ. Saf.* 154, 27–35. doi:10.1016/j.ecoenv.2018.02.006
- Zhang, Y., Chen, H., Jing, L., and Teng, Y. (2020b). Ecotoxicological Risk Assessment and Source Apportionment of Antibiotics in the Waters and Sediments of a Peri-Urban River. *Sci. Total Environ.* 731, 139128. doi:10.1016/j.scitotenv.2020.139128
- Zhang, Y., Rong, C., Song, Y., Wang, Y., Pei, J., Tang, X., et al. (2017). Oxidation of the Antibacterial Agent Norfloxacin during Sodium Hypochlorite Disinfection of marine Culture Water. *Chemosphere* 182, doi:10.1016/j.chemosphere.2017.05.023
- Zhang, Y., Wang, M., Zhang, D., Li, B., Bai, H., Zhang, H., et al. (2019a). Screening and Functional Identification of Cephalosporin Degrading Bacteria *Achromobacter* Sp. YF-1. *J. Agr. Sci. Tech-iran* 21, 112–119. doi:10.13304/j.nykjdb.2019.0257
- Zhang, Y., Yan, X., Sun, Y., Wu, H., and Lu, J. (2019). Current Situation of Antibiotic Abuse in China and its Residues Distribution in the Environment. *Contemp. Chem. Ind.* 48, 2660–2662.
- Zhang, Y., Zhang, G., Wang, Y., Liu, X., Bi, B., Liu, X., et al. (2021). Occurrence and Ecological Risk of Typical Antibiotics in Surface Water of the Lake SayramXinjiang. *J. Lake Sci.* 33, 483–493.
- Zhao, H., Liu, S., Chen, J., Jiang, J., Xie, Q., and Quan, X. (2015). Biological Uptake and Depuration of Sulfadiazine and Sulfamethoxazole in Common Carp (*Cyprinus carpio*). *Chemosphere* 120, 592–597. doi:10.1016/j.chemosphere.2014.09.075
- Zhao, L., Tan, S., Zhang, P., and Huang, T. (2016b). Effects of Different Organic Carbon Sources on Removal Efficiency of Tetracyclines from Wastewater in Constructed Wetlands. *Water Resour. Prot.* 32, 70–74. doi:10.3880/j.issn.1004-6933.2016.06.011

- Zhao, R., Li, X., Hu, M., Li, S., Zhai, Q., and Jiang, Y. (2017). Efficient Enzymatic Degradation Used as Pre-stage Treatment for Norfloxacin Removal by Activated Sludge. *Bioproc. Biosyst. Eng.* 40, 1261–1270. doi:10.1007/s00449-017-1786-y
- Zhao, S., Wang, X., Li, Y., and Lin, J. (2016a). Bioconcentration, Metabolism, and Biomarker Responses in marine Medaka (*Oryzias Melastigma*) Exposed to Sulfamethazine. *Aquat. Toxicol.* 181, 29–36. doi:10.1016/j.aquatox.2016.10.026
- Zheng, C., Wu, H., Li, F., and Du, W. (2017). Water Quality Evaluation of Typical Freshwater Aquaculture Area in Zhejiang Province. *J. Zhejiang Agric. Sci.* 58, 2268–2274. doi:10.16178/j.issn.0528-9017.20171258
- Zheng, H. (2017). Study on Distribution Characteristics and Health Risks of Some Antibiotics in Water Supply of a Water Plant, Huizhou City. *Prev. Med. Tribune* 23, 887–891. doi:10.16406/j.pmt.issn.1672-9153.2017.12.003
- Zhong, Y., Chen, Z.-F., Dai, X., Liu, S.-S., Zheng, G., Zhu, X., et al. (2018). Investigation of the Interaction between the Fate of Antibiotics in Aquafarms and Their Level in the Environment. *J. Environ. Manage.* 207, 219–229. doi:10.1016/j.jenvman.2017.11.030
- Zhou, W., Tang, Y., Du, X., Han, Y., Shi, W., Sun, S., et al. (2021). Fine Polystyrene Microplastics Render Immune Responses More Vulnerable to Two Veterinary Antibiotics in a Bivalve Species. *Mar. Pollut. Bull.* 164, 111995. doi:10.1016/j.marpolbul.2021.111995
- Zhu, T., Zhou, M., Yang, S., Wang, Z., Wang, R., Wang, W., et al. (2018). Occurrence and Ecological Risk of Sulfonamide Antibiotics in the Surface Water of the Weihe Xi'an Section. *Yellow River* 40, 85–91. doi:10.3969/j.issn.1000-1379.2018.12.020
- Zhu, X., Wang, X., Wang, L., Fan, X., Li, X., and Jiang, Y. (2020). Biodegradation of Lincomycin in Wastewater by Two-Level Bio-Treatment Using Chloroperoxidase and Activated Sludge: Degradation Route and Eco-Toxicity Evaluation. *Environ. Technology Innovation* 20, 101114. doi:10.1016/j.eti.2020.101114
- Zimmermann, P., and Curtis, N. (2020). Effect of Intrapartum Antibiotics on the Intestinal Microbiota of Infants: a Systematic Review. *Arch. Dis. Child. Fetal Neonatal. Ed.* 105, 201–208. doi:10.1136/archdischild-2018-316659

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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