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Occurrence and distribution of antibiotics in sediments from black-odor ditches in urban areas from China

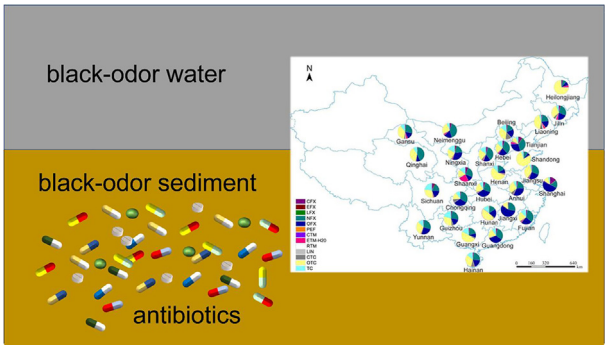
Yin-Zhi Lv [a,b], Xiao-Jun Luo [a,e,f,*], Jian-Liang Zhao [c], Shan-Quan Wang [d], Bi-Xian Mai [a,e,f]

[a] State Key Laboratory of Organic Geochemistry, Guangdong Key Laboratory of Environmental Resources Utilization and Protection, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] SCNU Environmental Research Institute, Guangdong Provincial Key Laboratory of Chemical Pollution and Environmental Safety & MOE Key Laboratory of Theoretical Chemistry of Environment, South China Normal University, Guangzhou 510006, China
[d] School of Environmental Science and Engineering, Sun Yat-Sen University, Guangzhou 510006, China
[e] Guangdong-Hong Kong-Macao Joint Laboratory for Environmental Pollution and Control, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[f] CAS Center for Excellence in Deep Earth Science, Guangzhou 510640, China

HIGHLIGHTS

- Antibiotics in black-odor sediments across China were investigated systematically for the first time.
- Totally 36 out of 44 antibiotics were detected in the sediment samples.
- Oxytetracycline, ofloxacin, norfloxacin and tetracycline were the dominant antibiotics.
- 12 antibiotic concentrations were positively related to total organic carbon.
- Significant correlations were found between some antibiotics from same or different classes.

GRAPHICAL ABSTRACT



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ABSTRACT

Antibiotic levels in black-odor water could reflect the usage amount of antibiotics in population. On the other hand, these antibiotics are the source of antibiotics in the environmental water. Currently, researches on antibiotics in black-odor sediments are still lacking. In this study, 174 black and odor sediment samples from 74 cities in 28 provinces in China were collected for analysis. Among 44 targeted antibiotics, 13 antibiotics were detected in more than 30% of sediment samples. Fluoroquinolones and tetracyclines were the predominant antibiotics in these field samples, with average concentrations of up to 2074 and 1902 ng/g dry weight (dw), respectively, followed by macrolides (87.9 ng/g dw), lincosamides (8.06 ng/g dw) and sulfonamides (8.38 ng/g dw). High antibiotic contamination levels were almost always detected in black-odor sludges from economically less developed small cities; however, the difference in antibiotic concentrations between well-developed and small cities in China was not statistically significant. In addition, among the seven regions within China, no significant difference in concentrations was observed for the most antibiotics. Variances in antibiotic composition patterns in the 28 provinces of China may be due to differences in bacterial resistance, prescription habits, efficacy, and sediment carbon concentrations among various regions. There were significant positive correlations among some antibiotics in the same or different classes.

* Corresponding author at: State Key Laboratory of Organic Geochemistry, Guangdong Key Laboratory of Environmental Resources Utilization and Protection, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China.
E-mail address: luoxiaoj@gig.ac.cn (X.-J. Luo).

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1. Introduction

Because of their distinct activity against bacteria, antibiotics have been widely used in human medicine, veterinary practices and aquaculture since the 1930s (Rodriguez-Mozaz et al., 2015). It is estimated that about 162,000 tons of antibiotics were consumed in China in 2013 (Zhang et al., 2015). Typically, antibiotics can be released into environmental water bodies from human, livestock, and aquaculture sources, including livestock farm effluents, feces and urine, medical wastewater, direct disposal of unused and expired medication into toilet, sewage treatment facilities and so on (Huang et al., 2019; Sarmah et al., 2006; Zhang et al., 2018). In urban areas, municipal sewage treatment system is an important source of antibiotics. However, antibiotics could only be partially removed in wastewater treatment plants (WWTPs), which are primarily designed for the removal of conventional pollutants such as nutrients and easily degradable organic contaminants. Hence, the unremoved antibiotics are ultimately disseminated into the receiving environment. Owing to their continuous input to the natural environment, antibiotics have been regarded as pseudo-persistent environmental pollutants and have elicited considerable concern (Llorca et al., 2015; Yao et al., 2015). Numerous recent studies have confirmed the presence of antibiotics in different environmental matrices, including water and sediments, WWTP influents and effluents, groundwater, sludge, soils, and animal manure (Fram and Belitz, 2011; Johnson et al., 2015; Zhang et al., 2018; Zhou et al., 2011).

Antibiotics in the natural environment are biologically active and can cause direct toxicity to non-target organisms (Wang et al., 2017). In addition, they can contribute to the development and dissemination of antibiotic-resistant bacteria or genes, which might result in more significant effects to the health of various organisms including humans and have been regarded as "emerging contaminants" (Christou et al., 2017; He et al., 2014). Studies have been conducted to investigate their environmental presence and evaluate their adverse ecological effects (He et al., 2019; Lu and Lu, 2019; Rodriguez-Mozaz et al., 2015; Yang et al., 2019). Simultaneously, parent antibiotics in the receiving environment may be transformed into diverse products owing to biological, physical, and chemical processes, and these transformation products might be more toxic or biologically active than their parent compounds (Michael et al., 2013; Onesios et al., 2009). Consequently, potentially hazardous effects of antibiotics on the ecological environment cannot be disregarded.

Following the rapid expansion of urbanization and industrialization, a significant number of environmental water bodies in urban areas of China have been severely polluted, many of which have even become black and malodorous (namely black-odor water bodies), thereby severely affecting the life quality and health of the local population (He et al., 2015; Wei et al., 2019). Generally, black-odor water bodies collectively refer to water bodies that present unpleasant colors and/or emit foul smell (MOHURD, 2015). By 2016, the phenomenon of black and smelly water had occurred in 216 out of the 295 prefecture-level and above cities in China, and the total number of black-odor water bodies in the country had reached 1811 (MOHURD, 2016). The formation of black-odor water is primarily caused by exogenous pollution (domestic sewage, industrial wastewater, surface runoff, etc.) and endogenous pollution (sediment pollution, organism pollution, etc.). As both "sinks" and "sources" of water pollutants, sediments can not only adsorb various inorganic or organic contaminants from the overlying water, but also release contaminants into the water when environmental factors (e.g. water flow, pH, and temperature, etc.) change (Ao et al., 2018; Cheng et al., 2014). Therefore, sediment pollution plays an important role in endogenous pollution of black-odor water and should be of concern. So far, many studies have reported the existence and distribution of antibiotics in river sediments, lake sediments and marine sediments (Cheng et al., 2016; Li et al., 2018; Xu et al., 2018); however, the antibiotic contamination in black-odor sediments (i.e., the surface sediments in black-odor water) in China remains unclear.

In this work, sediment samples were collected from the major urban black-odor water bodies in China to investigate the occurrence and distribution of 44 target antibiotics in black-odor sediment nationwide, as well as to provide a basic understanding regarding the antibiotic contamination of black-odor sediments in China. To the best of our knowledge, this is the first report pertaining to the concentration of antibiotics in sediments from urban black-odor water across China.

2. Materials and methods

2.1. Chemicals and materials

The abbreviations of the target antibiotics were displayed in Table 1. In total, seven classes of 44 antibiotics, including 3 subtypes of IPs, 1 subtype of AGs, 17 subtypes of SAs, 12 subtypes of FQs, 5 subtypes of MLs, 1 subtype of LMs, and 5 subtypes of TCs were selected for this study. NAR was obtained from US Pharmacopoeia (Rockville, MD), whereas SMR was purchased from Dr. Ehrenstorfer GmbH (Germany). SAL, MON, NOV, LIN, CTM, LCM, the FQs, the TCs, and the 16 other subtypes of SAs were supplied by Dr. Ehrenstorfer GmbH (Germany). ETM, RTM, and TYL were purchased from Sigma-Aldrich (St. Louis, MO, USA). ETM-H_2O was prepared by acidification, which can be referred to a previous report (Xu et al., 2007). Six isotope-labeled internal standards, i.e., sulfamethoxazole-D_4, thiabendazole-D_4, trimethoprim-D_3, ciprofloxacin-D_8, erythromycin-^{13}C-D_3, and lincomycin-D_3 were supplied by Toronto Research Chemicals (North York, ON, Canada), whereas meclocycline and sulfamethazine-$^{13}C_6$ were purchased from Sigma–Aldrich (St. Louis, MO, USA) and Cambridge Isotope Laboratories (Andover, MA, USA), respectively.

Methanol, acetonitrile, formic acid, and ammonium acetate were of HPLC grade; the first two were obtained from Merck (Darmstadt, Germany), and the last two were obtained from Aladdin Bio-Chem Technology Co., LTD (Shanghai, China) and CNW Technologies (Germany), respectively. Citric acid, trisodium citrate dihydrate, and tetrasodium ethylenediaminetetraacetate (Na_4EDTA) were of analytical grade and purchased from the Damao Chemical Reagent Factory (Tianjin, China). Strong anion exchange (SAX) cartridges (6 mL, 500 mg) and Oasis HLB cartridges (6 mL, 200 mg) were provided by Agilent Technology (Palo Alto, USA) and Waters (Milford, MA, USA), respectively.

2.2. Study area and sample collection

In this study, 28 among 34 provincial administrative regions in China were investigated. Based on their geographical characteristics, the 28 provinces can be classified into seven regions: East China (Shanghai, Jiangsu, Anhui, Fujian, Jiangxi, and Shandong Province), North China (Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia Province), Central China (Henan, Hubei, and Hunan Province), South China (Guangdong, Guangxi, and Hainan Province), Northeast China (Liaoning, Jilin, and Heilongjiang Province), Northwest China (Shaanxi, Gansu, Qinghai, and Ningxia Province), and Southwest China (Chongqing, Sichuan, Guizhou, and Yunnan Province). A total of 174 black-odor sediment samples were collected from 74 cities within the 28 provinces in 2018 (Fig. S1). Detailed information regarding the sampling sites is provided in Table S1.

All the sediment samples were collected and stored in pre-cleaned glass containers, with 2 g of sodium azide added immediately to inhibit microbial activity. After arriving at the laboratory, the samples were freeze-dried, ground, homogenized by passing through an 80 mesh standard sieve and then stored at −18 °C in the dark until further extraction. The total organic carbon (TOC) of the sediment samples was determined using an elemental analyzer (Vario EL, Elementar, GmbH, Germany) after the removal of inorganics using hydrochloric acid.

Table 1
Concentrations (ng/g dry weight) of the antibiotics in Chinese black-odor sediment.

Compounds	Abbreviation	N[a]	Range	Median	Mean
Fluoroquinolones	FQs				
Ciprofloxacin	CFX	172	0.85–1908	65.4	118
Danofloxacin	DAN	13	1.56–2.65	1.61	1.69
Difloxacin	DIF	10	0.92–105	1.11	11.8
Enrofloxacin	EFX	138	0.59–850	4.42	19.0
Fleroxacin	FL	29	0.94–12.8	1.77	2.70
Lomefloxacin	LFX	98	0.40–180	6.11	12.2
Marbofloxacin	MAR	1	1.04		
Norfloxacin	NFX	170	1.08–20,690	519	1003
Ofloxacin	OFX	166	1.53–26,840	450	976
Pefloxacin	PEF	143	0.86–468	4.79	13.9
Sarafloxacin	SAR	5	1.28–32.3	2.55	13.3
Carbadox	CAR	1	1.97		
∑FQs[b]		**173**	**2.00–50,190**	**1034**	**2074**
Macrolides	MLs				
Clarithromycin	CTM	68	0.38–82.7	2.54	8.80
Erythromycin-H_2O	ETM- H_2O	167	0.39–1077	18.8	66.5
Leucomycin	LCM	3	1.15–4.77	2.82	2.91
Roxithromycin	RTM	114	0.66–379	7.74	25.9
Tylosin	TYL	2	5.70, 11.2		
∑MLs		**167**	**0.39–1142**	**25.5**	**87.9**
Lincosamides	LMs				
Lincomycin	**LIN**	**139**	**0.94–86.5**	**4.41**	**8.06**
Tetracyclines	TCs				
Chlortetracycline	CTC	124	2.82–937	30.9	99.7
Doxycycline	DC	25	12.9–524	78.8	115
Methacycline	MT	47	0.63–30.6	2.07	4.02
Oxytetracycline	OTC	174	1.47–22,590	540	1388
Tetracycline	TC	170	1.46–7160	186	435
∑TCs		**174**	**4.95–29,930**	**778**	**1902**
Sulfonamides	SAs				
Sulfacetamide	SCT	ND[c]			
Sulfachlorpyridazine	SCP	2	0.50, 1.06		
Sulfadiazine	SDZ	15	0.23–18.4	0.51	2.28
Sulfadoxine	SDO	1	8.99		
Sulfadimethoxine	SDM	1	36		
Sulfaguanidine	SG	ND			
Sulfamethazine	SMZ	14	0.41–10.8	2.48	3.39
Sulfamethoxazole	SMX	ND			
Sulfameter	SM	1	2.65		
Sulfamonomethoxine	SMM	16	0.58–15.4	1.63	4.22
Sulfapyridine	SPD	8	0.82–6.15	2.06	2.50
Sulfaquinoxaline	SQX	ND			
Sulfisoxazole	SX	2	0.52, 0.57		
Sulfathiazole	STZ	5	0.76–33.9	3.42	9.42
Sulfamerazine	SMR	3	0.72–2.15	1.12	1.33
Ormetoprim	OMP	2	2.84, 50.3		
Trimethoprim	TMP	42	0.51–26.8	2.31	4.66
∑SAs		**62**	**0.23–148**	**2.89**	**8.38**
Ionophores	IPs				
Monensin	MON	ND			
Narasin	NAR	ND			
Salinomycin	SAL	ND			
∑IPs		**ND**			
Aminoglycoside	AGs				
Novobiocin	NOV	ND			
∑AGs		**ND**			

[a] N: detection number.
[b] ΣFQs: the sum of FQs, similarly hereinafter.
[c] ND: not detected.

2.3. Sample extraction

The sample extraction and clean-up performed in this study was based on a previously reported method (Zhou et al., 2012). Briefly, the prepared sediment sample (2 g each) was weighed and added into a 30 mL glass centrifuge tube, spiked with 100 μL of internal standard mixture (1.0 mg/L). Next, the sample was mixed homogeneously and stored at 4 °C overnight. Subsequently, each sample was mixed with 10 mL of citric acid buffer (pH = 3) and 10 mL of acetonitrile and then ultrasonicated for 15 min. After the sample was centrifuged for 10 min at 1370*g*, the supernatant of each tube was collected into a round-bottom glass flask (200 mL). The extraction process above was conducted for two additional times, and the supernatants from the three extractions were collected together. The combined extract from each sample was spin-evaporated at 55 °C to get rid of the organic phase. Prior to solid phase extraction, 0.2 g of Na_4EDTA was added into each concentrated aqueous phase extract, followed by dilution to 200 mL with Milli-Q water. After being mixed homogeneously, the diluted extract was loaded at a flow rate of 5 mL/min in the SAX-HLB tandem cartridges preconditioned by consecutively passing 10 mL methanol and 10 mL Milli-Q water through it previously. Subsequently, the SAX cartridge was removed, and 10 mL of Milli-Q water was added to the HLB cartridge to eliminate Na_4EDTA and other impurities. After the cartridge was dried under vacuum, the elution was implemented with 10 mL of methanol, and the eluate was collected and concentrated to near dryness under a gentle nitrogen stream. Each dried extract was reconstituted into 1 mL of methanol, mixed, filtered through a 0.22 μm nylon membrane filter, and finally kept at −18 °C until further analysis.

2.4. Instrumental analysis

The instrument analysis of the antibiotics was performed with an 1290 Infinity II series ultrahigh performance liquid chromatograph coupled to Agilent 6495 triple quadrupole mass spectrometer (UHPLC-MS/MS) equipped with an electrospray ionization (ESI+) source. The chromatographic separation of target antibiotics was performed on an Agilent Eclipse Plus-C18 RRHD column (100 mm × 2.1 mm, 1.8 μm) with a corresponding guard column. The column temperature was maintained at 40 °C. The injection volume and the flow rate were set to 10 μL and 0.3 mL/min, respectively. The mobile phase consisted of water containing 2 mM ammonium acetate and 0.2% (*v*/v) formic acid (A) and acetonitrile (B). The gradient elution program was programmed as follows: ramped from 10%–15% B in 5 min, from 15%–20% B in 2 min, from 20%–40% B in 4 min, from 40%–60% B in 4 min, and from 60%–95% B in 1 min (holding 95% B for 4 min), with a post-time of 6 min. Detection was operated in multiple reaction monitoring (MRM) mode, with main MS parameters as follows: drying gas (Nitrogen) flow rate and temperature were 11 mL/min and 280 °C, respectively. The nebulizer pressure was set to 20 psi. The sheath gas flow rate and temperature were held at 11 mL/min and 250 °C, respectively. The capillary voltage was 3000 V. MRM parameters for the target antibiotics were listed in Table S2. Quantification of the target analytes was carried out with the internal calibration method, and a six-point calibration curve was constructed for individual chemicals at concentrations ranging from 1.0 to 200 μg/L.

2.5. Quality assurance and quality control (QA/QC) and data analysis

QA/QC procedures were performed throughout the sampling, pretreatment, and instrument analysis. Analyses of spiked blank samples, spiked matrix samples, and procedural blank samples were included. Simultaneously, a solvent blank and an independent check standard (100 μg/L for each compound) for each batch of 15 samples were processed in sequence to monitor background pollution and the performance of instrument. No target antibiotics were found in procedural blank or solvent blank samples. The method detection limits (MDLs) and quantification limits (MQLs) of the target antibiotics were set as the signal-to-noise ratios of 3 and 10 times, respectively. Detailed MDLs, MQLs, mean recoveries, and mean matrix effects for 44 individual compounds in black-odor sediments are summarized in Table S3.

In this study, data analysis was conducted using Microsoft Excel 2019, Origin Pro 9.0.0, and IBM SPSS Statistics 25 software. The antibiotic concentrations were reported as dry weight (dw). Concentration values below the MQLs were considered to be not detected. Kruskal-Wallis test (K—W test) was used to compare antibiotic levels among different cities and regions in China. The correlations between antibiotic

levels and TOC and among antibiotic levels were examined with Pearson's correlation analysis. The Kolmogorov-Smirnov test was performed prior to the statistical analysis, and the results revealed that these data didn't fit normal distribution. Therefore, the raw data (antibiotic concentrations and TOC values) were transformed to logarithmic values for the Pearson's correlation analysis. The level of significance was defined as $p \leq 0.05$ in the present study.

3. Results and discussion

3.1. Occurrence of antibiotics in urban black-odor sediment of China

Descriptive statistics for the detected concentrations of the selected antibiotics in this study were summarized in Table 1. Antibiotics were detected in all the 174 field samples, indicating widespread contamination of these compounds in black-odor sludges throughout China. Among the seven classes of antibiotics detected, five classes of antibiotics (FQs, MLs, LMs, TCs, and SAs) were found in different degrees in these samples, whereas IPs and AGs were not detected in any sediment sample. Although up to 37 antibiotics were detected in the sediment samples, many of them (DAN, DIF, FL, MAR, SAR, CAR, LCM, TYL, DC, MT, and the 13 subtypes of SAs) occurred in less than one-third of the samples (detection number < 58) and tended to be low in concentrations (Table 1). The relatively low frequencies and low levels of these compounds in sediments could be related to their low usage (Zhang et al., 2015), great degradation performance (Loke et al., 2000; Sturini et al., 2010; Sturini et al., 2012a; Sturini et al., 2012b), and/or strong hydrophilic nature (Zhang et al., 2018). Only 13 antibiotics with a detection frequency exceeding 1/3 were discussed hereinafter; those antibiotics include six subtypes of FQs (CFX, EFX, LFX, NFX, OFX, and PEF), three subtypes of TCs (CTC, OTC, and TC), three subtypes of MLs (CTM, ETM-H_2O, and RTM), and LIN.

The concentrations of detected ∑FQs (i.e., the sum of FQs, similarly hereinafter) and ∑TCs ranged from 2.00 to 50,190 ng/g with a median of 1034 ng/g and from 4.95 to 29,930 ng/g with a median of 778 ng/g, respectively; while ∑MLs, ∑LMs, and ∑SAs were found in much lower concentrations, ranging from 0.39 to 1142 ng/g with a median of 25.5 ng/g, from 0.94 to 86.5 ng/g with a median of 4.41 ng/g, and from 0.23 to 148 ng/g with a median of 2.89 ng/g, respectively (Table 1). The concentrations of ∑FQs and ∑TCs were one to three orders of magnitude higher than those of ∑MLs, ∑LMs, and ∑SAs (Table 1). This result may be due to the stronger adsorption on solid phases (sludge, sediments, particles, etc.) of FQs and TCs than other antibiotics (Kummerer, 2009; Li et al., 2018). Similarly, previous studies have shown that FQs and TCs were predominant, being significantly higher in concentration than other antibiotics in different river sediments (Huang et al., 2019; Zhou et al., 2011). However, in environmental water, the concentrations of FQs and TCs were much lower or even below their MQLs (Xu et al., 2009; Yang et al., 2011). All of these reports suggest that sediments are a significant sink for FQs and TCs.

Among the six subtypes of FQs, NFX (Fig. 1D) and OFX (Fig. 1F) were the most prevalent pollutants, followed by CFX (Fig. 1A), EFX (Fig. 1B), LFX (Fig. 1C) and PEF (Fig. 1E). Similar results have been reported in previous researches (Huang et al., 2019; Zhou et al., 2011). NFX and OFX were detected in more than 166 of 174 field samples, with maximum average concentrations of 11,840 and 15,370 ng/g in Shantou, respectively (Table 1 and S4). The second highest concentrations (7775 and 6250 ng/g, respectively) were found in Shenzhen, which has a dense population and developed economy (Table S4). The notable abundance was not unexpected, as the usage of these two antibiotics in China is prevalent. For example, the amounts of NFX and OFX used in 2013 were 5440 and 5110 tons, respectively (Zhang et al., 2015). CFX was also found in a high frequency (99%) with the concentration range of 0.85–1908 ng/g (Table 1). Similar to NFX and OFX, the relatively high average levels of CFX were also detected in Shantou (1186 ng/g) and Shenzhen (802 ng/g) (Table S4). By contrast, the detectable frequencies of EFX, LFX, and PEF were 79%, 56%, and 82%, respectively, and their concentrations ranged from 0.59–850 ng/g with a mean value of 19.0 ng/g, from 0.4–180 ng/g with a mean value of 12.2 ng/g, and from 0.86–468 ng/g with a mean value of 13.9 ng/g, respectively (Table 1). EFX is an antibiotic that is used specifically in animals and was found in the present study with average concentrations of more than 100 ng/g in only three cities (Neijiang, 440 ng/g; Nanning, 109 ng/g; and Jilin, 108 ng/g) (Table S4). The present results indicated the probable role of poultry, livestock, or the aquaculture industry in the three cities as important sources of EFX contamination. The highest levels of LFX and PEF were detected in Shantou, which were 97.3 and 239 ng/g, respectively (Table S4). Their low usage was responsible for their low detection rate (Zhang et al., 2015).

Among the three subtypes of TCs mentioned above, OTC was found in all 174 samples at considerably high levels (1.47–22,590 ng/g) (Fig. 2F and Table 1). TC was detected in 98% of the samples. The concentrations of TC (Fig. 2G and Table 1) were lower than those of OTC, ranging from 1.46 to 7160 ng/g. Spatially, OTC was detected in Heze at the highest average concentration of 12,540 ng/g. Besides, high concentrations of OTC and TC were found in Shantou and Yongzhou with average levels of 7355 and 12,050 ng/g for OTC, and of 3773 and 3764 ng/g for TC, respectively (Table S4). The detectable frequency of CTC was 71%, and the concentration range of CTC was 2.82–937 ng/g (Fig. 2E and Table 1), which was obviously lower than those of OTC and TC. Similar results could be found in previous studies (Huang et al., 2019; Jia et al., 2018).

The levels of the three subtypes of MLs in black and odor sludge from all of the 28 provincial administrative regions of China were in the following order: ETM-H_2O (Fig. 2B) > RTM (Fig. 2C) > CTM (Fig. 2A). Generally, the concentrations of RTM (median: 7.74 ng/g) and CTM (2.54 ng/g) in the samples were about one order of magnitude lower than those of ETM-H_2O (18.8 ng/g) (Table S4). The difference in their abundance was consistent with those of their usage quantities in China (Zhang et al., 2015). ETM-H_2O was found in 96% of all the samples, and the sample collected from Weinan presented the highest level (1077 ng/g) (Table 1 and S4). In addition, relatively high mean values of ETM-H_2O (218 to 277 ng/g) were found in Hohhot, Shantou, Tianshui, Changchun, and Siping (Table S4). RTM was measured in black-odor sludge with a moderate frequency of 66%, and only samples from Changchun and Shenyang had relatively high mean concentrations of more than 100 ng/g (Table 1 and S4). CTM was detected in 68 among the 174 samples with the highest average concentration in Tianjin (less than 30 ng/g) (Tables 1 and S4). Large variations in the distribution of the three subtypes of MLs in China suggest differences in antibiotic usage strategies among these cities.

As an antibiotic typically used in human medicine, animal husbandry, and aquaculture, the annual consumption of LIN is huge (Zhang et al., 2015; Zhang et al., 2018). However, LIN was found in this study at relatively low concentrations ranging from 0.94 to 86.5 ng/g, despite its significant frequency of 80% (Fig. 2D and Table 1). This is probably because of the degradation of LIN in water and sediments (Lei and Lai, 2018).

In addition to black-odor sediments, WWTPs sludge is also an important source of antibiotics in environmental water. Therefore, the antibiotic concentrations in black-odor sediment and WWTPs sludge in China were compared (Table S5). A few sediment samples in this study contained extremely high levels of antibiotic. For example, up to 1908, 850, 26,840, 468, 1077, 22,590, and 7160 ng/g for CFX, EFX, OFX, PEF, ETM-H_2O, OTC, and TC, respectively, were detected in the present study; these levels were much higher than the maximum concentrations of the corresponding antibiotic in Chinese WWTPs sludge (Table S5). In terms of average concentration, however, the antibiotic levels in the black-odor sediments from our study were lower than or comparable to those in WWTPs sludge from other researches (Ashfaq et al., 2017; Li et al., 2013; Zhou et al., 2012; Zhou et al., 2013; Zhou et al., 2019). This suggests that the antibiotic contamination levels in

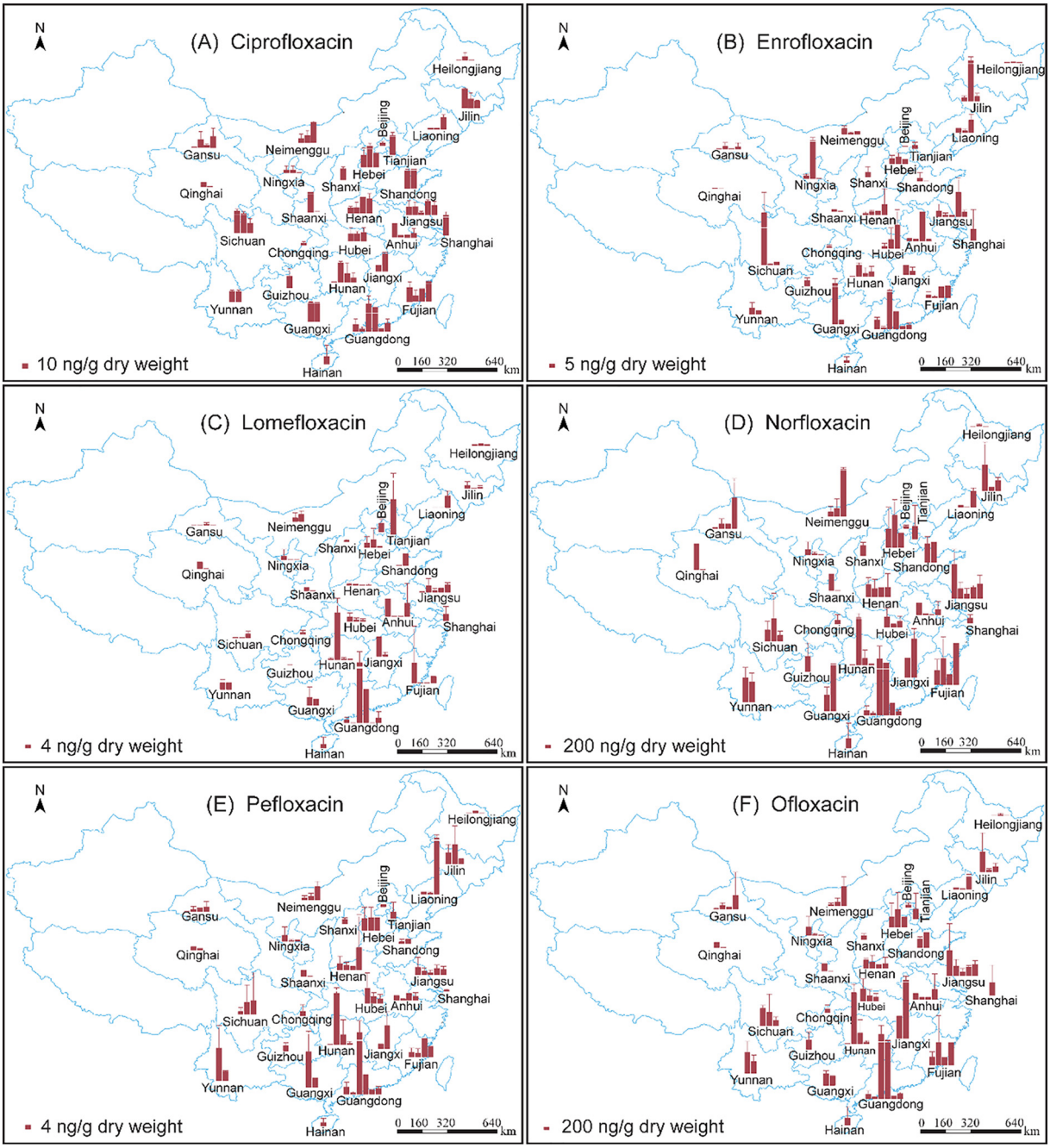

Fig. 1. The distribution of the six target subtypes of FQs (A–F) in the black-odor sediment samples from China. (Different bars in every province represent the corresponding sampling cities. The details are as follows. Hebei: Shijiazhuang, Handan, Qinhuangdao (from left bar to right bar, the same below). Beijing: Beijing. Tianjin: Tianjin. Shanxi: Taiyuan. Neimenggu: Bayannaoer, Baotou, Hohhot. Henan: Xinyang, Zhengzhou, Anyang, Kaifeng. Hubei: Wuhan, Jingzhou, Suizhou. Hunan: Hengyang, Yongzhou, Changsha, Yueyang. Guangxi: Nanning, Guigang. Guangdong: Zhanjiang, Yangjiang, Shantou, Shenzhen, Huizhou, Guangzhou. Hainan: Haiou. Shanghai: Shanghai. Anhui: Fuyang, Hefei, Maanshan, Wuhu. Jiangsu: Xuzhou, Nanjing, Yangzhou, Nantong, Wuxi. Jiangxi: Shangrao, Nanchang. Fujian: Fuzhou, Xiamen, Longyan, Zhangzhou. Shandong: Heze, Linyi. Ningxia: Yinchuan, Wuzhong, Shizuishan. Gansu: Dunhuang, Zhangye, Lanzhou, Tianshui. Qinghai: Delingha, Xining. Shaanxi: Weinan, Xi'an. Yunnan: Kunming, Yuxi. Chongqing: Chongqing. Sichuan: Neijiang, Guangyuan, Chengdu. Guizhou: Anshun. Jilin: Changchun, Jilin, Siping. Liaoning: Huludao, Yingkou, Shenyang. Heilongjiang: Qiqihaer, Daqing, Haerbin.)

the most black-odor sediment samples were comparable to those in most WWTPs sludge samples. In addition, Huang et al. (2019) investigated antibiotic concentrations in black-odor sludge from Guangzhou, and their result were similar to those reported in our study.

3.2. Spatial distribution of antibiotics in Chinese black and odor sludge

Generally speaking, the levels of antibiotic in black and odor sludges varied greatly among the 74 cities in China. As mentioned above, high levels of antibiotic were detected in black-odor sludge samples from Shenzhen, Nanning, Changchun, Hohhot, Yongzhou, Shantou, Tianshui, Weinan, Neijiang, Jilin, Siping, and Heze. Except for Shenzhen, the economic development levels of most the other cities is relatively weak. By contrast, the samples collected from Haerbin and Chongqing contained extremely low levels of all the 13 antibiotics (Figs. 1 and 2). Meanwhile, it is noteworthy that antibiotic concentrations found in Beijing, Shanghai, and Guangzhou were particularly low, which was inconsistent with their developed economies and dense populations. These results indicated a possible negative correlation between antibiotic use and the regional economy. Furthermore, the 74 sampling cities

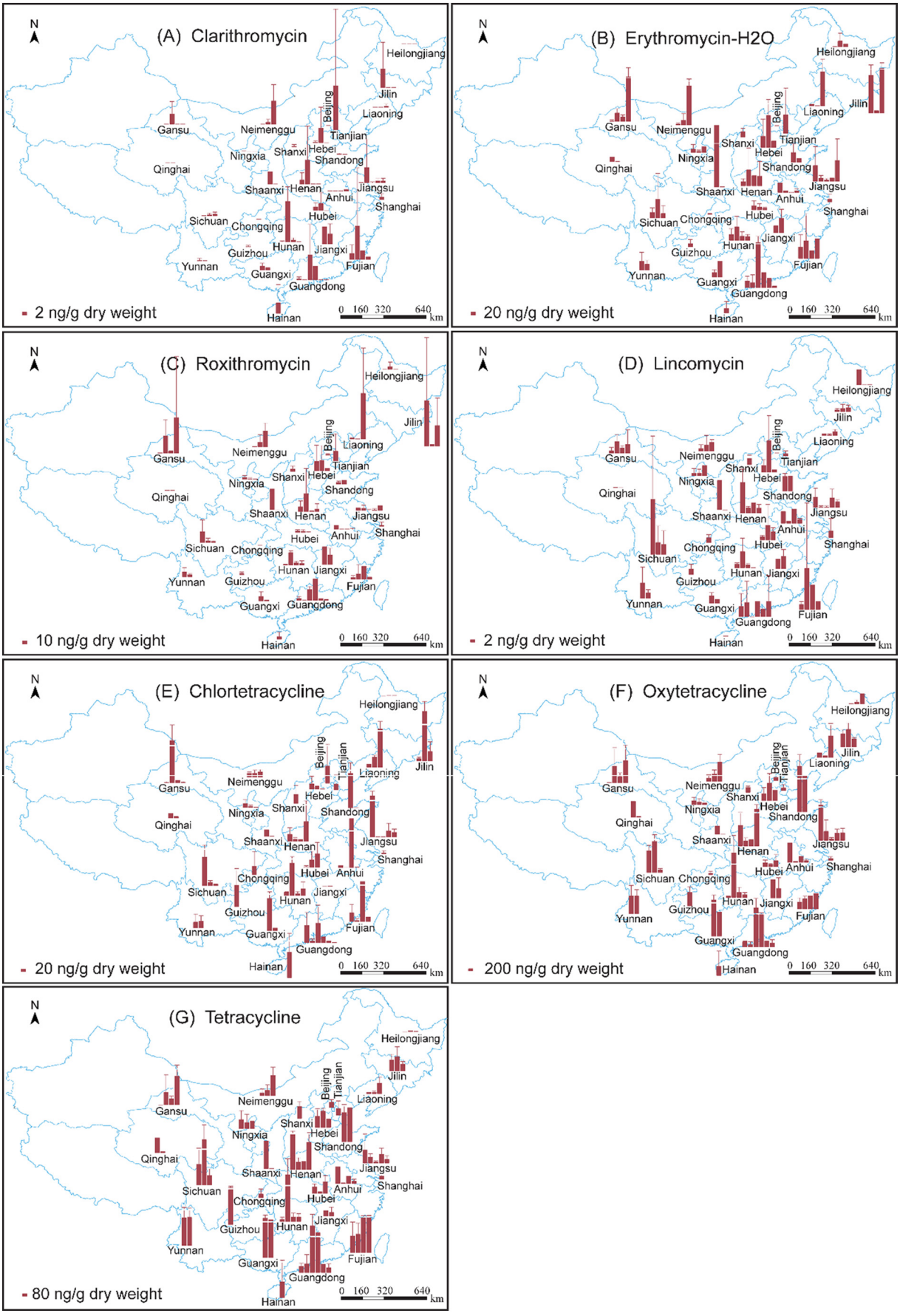

Fig. 2. The distribution of the three subtypes of MLs (A, B and C), LIN (D), and three subtypes of TCs (E, F and G) in the black-odor sediment samples from China. The explanations are same as Fig. 1.

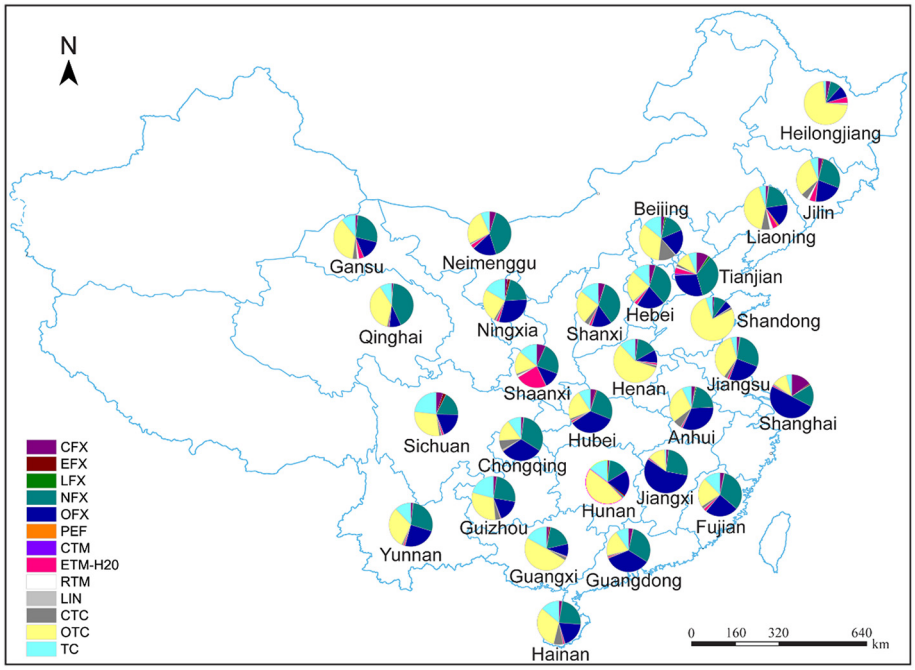

Fig. 3. Composition (%) of the select antibiotics in black-odor sediments of different provinces in China.

were classified into three categories based on the level of economic development as follows: first-tier cities, second-tier cities and small cities. As shown in Fig. S2, high concentrations of antibiotics were almost always detected in black-odor sludge from economically less developed small cities, whereas the first/second-tier cities tended to contain relatively low antibiotic levels, with the exception of two cities (Shenzhen and Nanning). However, the results of the K—W test showed that no significant concentration difference among the three types of cities ($p > 0.05$). Therefore, the relationship between antibiotic usage and urban scale remains unclear. Considering a previous survey (Gu et al., 2015), that revealed the tendency of urban inhabitants and those with higher education levels to consume antibiotics more reasonably, further research is needed on possible differences in antibiotic usage between large and small cities.

In terms of geographical characteristics, TCs were mainly distributed in East China, Central China, and South China (Fig. S3D), whereas MLs were mainly in Northeast China, North China, and Northwest China (Fig. S3B). No obvious geographical distribution characteristics were found for FQs and LMs (Fig. S3A and C). To further analyze the geographical characteristics, the K—W test was conducted to identify the differences in individual antibiotic distributions among the seven regions. Obvious spatial differences were observed for CFX, EFX, LFX, NFX, and OFX ($p < 0.05$). As shown in Fig. S4, the levels in Northwest China for the five compounds were relatively lower than those in the other six regions. However, for the other eight antibiotics, there was no significant difference among the seven regions ($p > 0.05$), indicating that the use of these antibiotics in China did not exhibit clear large-region characteristics.

3.3. Antibiotic contaminant patterns

The composition of antibiotics in the sediment samples was shown in Fig. 3. It can be seen that OTC, OFX, NFX, and TC were the main pollutants in almost all the provinces, constituted 11%–77%, 5.4%–56.5%, 8%–41%, and 1%–23% of the total antibiotics, respectively. ETM-H_2O, CFX and CTC had similar contributions (less than 7%) to the total amounts of antibiotics in individual provinces, despite some exceptions for ETM-H_2O in Shaanxi Province (23%), CFX in Shanghai (15%) and Tianjin (9%), and CTC in Beijing (13%). The contribution rate of RTM, EFX, LFX, PEF, CTM, or LIN to the total amounts of antibiotics was less than 2.3% in all the provinces. Basically, there were some variances in the antibiotic composition patterns for the 28 provinces of China.

In fact, depending on a patient's specific constitution, symptoms, and economic conditions, different antibiotics may be required to treat a specific bacterial infection. Likewise, a combination of different antibiotics can be used to treat different bacterial infections. Accordingly, differences in bacterial resistance, price, prescription habits and efficacy might be the primary reasons for the discrepancies in the composition profiles of antibiotics in various regions.

Moreover, 12 antibiotics were found to be significantly related to TOC in sediment samples in this work ($0.35 < r < 0.6$) (Fig. S5), implying organic carbon content in sediment may be a contributing factor to the diverse composition profiles.

3.4. Correlation analysis among antibiotics

Correlation analysis was conducted on the logarithmic values of the antibiotic concentrations to demonstrate the relationships among different antibiotics (Figs. S6 and S7). There were statistically significant correlations among the FQs (Fig. S6A—F). Thereinto, good positive correlations were observed among CFX, NFX, and OFX ($r > 0.88$) (Fig. S6A—C), all of which are used frequently in clinical treatment. However, the correlations among the other FQs as well as between CFX, NFX, or OFX and all the other FQs were moderate or relatively weak ($r < 0.67$). In particular, the correlation coefficient between EFX and CFX was 0.51 (Fig. S6D). It is known that EFX can transform into CFX in water environments (Kerrigan et al., 2018); hence, the low correlation between them suggests that most of CFX were not originated from metabolism of EFX, and off-the-shelf commercial CFX is the likely source of pollution for the black and smelly sludge in the present study area. In addition, EFX concentrations reported in a previous study were highly correlated with those of OFX and CFX (Qian et al., 2016), which is inconsistent with our study. Antibiotic sources may be responsible for the divergence. Specifically speaking, most of the black and smelly sludge samples in this study were collected from

city areas, where humans were the main source of antibiotic emissions. While in the previous study (Qian et al., 2016), animals manures were the main antibiotics source. Accordingly, correlation analysis may be used to determine whether antibiotics come from human or animal sources.

For TCs, a significant positive relationship was exhibited between OTC and TC ($r = 0.85$) (Fig. S6J), but weak correlations were exhibited between CTC and OTC or TC ($r < 0.5$) (Fig. S6K and L). Both OTC and TC have the same antibacterial spectrum and can be used to treat rickettsial disease, mycoplasma infection, and chlamydia infection etc. However, because of its significant side effects, CTC is currently only for external use, such as for the treatment of conjunctivitis and trachoma. As for MLs, the concentrations of ETM-H_2O were highly correlated with those of RTM ($r = 0.79$) (Fig. S6G); however, relatively moderate correlations ($r = 0.52$ and 0.60) were found between ETM-H_2O or RTM and CTM (Fig. S6H and I). The current results indicated that there may be some differences in usage patterns or environmental behaviors (e.g. degradation characteristics, etc.) between CTM and the other two subtypes of MLs.

Correlations among the four different classes of antibiotics (FQs, MLs, LIN and TCs) were also examined, and the results showed that there were significant positive correlations between several antibiotics from different classes (Fig. S7). For example, TC and OTC were highly positively related to CFX, OFX, and NFX ($r \geq 0.69$) (Fig. S7A—F). Significant positive correlations were also found between OTC or TC and ETM-H_2O ($r = 0.66$ and 0.60) (Fig. S7G and H). The above results suggested that there were more or less links (such as combined drug treatment, etc.) among these antibiotics in clinical use.

4. Conclusion

The present study provides important basic data regarding the presence and distribution of antibiotics in Chinese black-odor sediments. In summary, extensive antibiotic contamination was found in black-odor sludge throughout China. OTC, OFX, NFX, and TC were the predominant antibiotics detected in the sediment samples. More severe antibiotic pollution was found in economically underdeveloped areas than in large cities in China, although these differences were not statistically significant. In addition, no significant concentration difference was found among the seven regions of China for the most antibiotics. The usage strategy of antibiotics may depend on prescription habits, antibiotic price, efficacy, and bacterial resistance in local areas. In conclusion, the detection of various antibiotics with high concentrations in black-odor sludge indicated that these sludge are an important reservoir of antibiotic residues in the aquatic environment. Notably, the antibiotics adsorbed in the sediments are still biologically active to some extent and can be released into water under suitable conditions, thereby affecting the stability and function of the water ecosystem. Therefore, understanding the presence and distribution of antibiotics in black-odor sludge can facilitate the assessment of their environmental risks and proposal of effective management strategies.

CRediT authorship contribution statement

Yin-Zhi Lv: Conceptualization, Formal analysis, Validation, Visualization, Writing – original draft. **Xiao-Jun Luo:** Supervision, Writing – review & editing. **Jian-Liang Zhao:** Resources. **Shan-Quan Wang:** Resources. **Bi-Xian Mai:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147554.

References

Ao, D., Chen, R., Wang, X.C., Liu, Y., Dzakpasu, M., Zhang, L., Huang, Y., Xue, T., Wang, N., 2018. On the risks from sediment and overlying water by replenishing urban landscape ponds with reclaimed wastewater. Environ. Pollut. 236, 488–497.

Ashfaq, M., Li, Y., Wang, Y.W., Chen, W.J., Wang, H., Chen, X.Q., Wu, W., Huang, Z.Y., Yu, C.P., Sun, Q., 2017. Occurrence, fate, and mass balance of different classes of pharmaceuticals and personal care products in an anaerobic-anoxic-oxic wastewater treatment plant in Xiamen, China. Water Res. 123, 655–667.

Cheng, D.M., Liu, X.H., Wang, L., Gong, W.W., Liu, G.N., Fu, W.J., Cheng, M., 2014. Seasonal variation and sediment-water exchange of antibiotics in a shallower large lake in North China. Sci. Total Environ. 476–477, 266–275.

Cheng, D.M., Xie, Y.J., Yu, Y.J., Liu, X.H., Zhao, S.N., Cui, B.S., Bai, J.H., 2016. Occurrence and partitioning of antibiotics in the water column and bottom sediments from the intertidal zone in the Bohai Bay, China. Wetlands 36, S167–S179.

Christou, A., Aguera, A., Bayona, J.M., Cytryn, E., Fotopoulos, V., Lambropoulou, D., Manaia, C.M., Michael, C., Revitt, M., Schroder, P., Fatta-Kassinos, D., 2017. The potential implications of reclaimed wastewater reuse for irrigation on the agricultural environment: the knowns and unknowns of the fate of antibiotics and antibiotic resistant bacteria and resistance genes-a review. Water Res. 123, 448–467.

Fram, M.S., Belitz, K., 2011. Occurrence and concentrations of pharmaceutical compounds in groundwater used for public drinking-water supply in California. Sci. Total Environ. 409, 3409–3417.

Gu, J.R., Zhao, J.Z., Huang, Y., Yang, W.D., Ren, Z., Li, W.J., Fan, Y.Z., Zhang, Q., Zhang, F.M., Fu, Y.M., 2015. Use of antibiotics by urban and rural residents in Heilongjiang Province, China: cross-sectional study. Tropical Med. Int. Health 20, 1815–1822.

He, L.Y., Liu, Y.S., Su, H.C., Zhao, J.L., Liu, S.S., Chen, J., Liu, W.R., Ying, G.G., 2014. Dissemination of antibiotic resistance genes in representative broiler feedlots environments: identification of indicator ARGs and correlations with environmental variables. Environ. Sci. Technol. 48, 13120–13129.

He, D.F., Chen, R.R., Zhu, E.H., Chen, N., Yang, B., Shi, H.H., Huang, M.S., 2015. Toxicity bioassays for water from black-odor rivers in Wenzhou, China. Environ. Sci. Pollut. Res. Int. 22, 1731–1741.

He, P.J., Yu, Z.F., Shao, L.M., Zhou, Y.Z., Lu, F., 2019. Fate of antibiotics and antibiotic resistance genes in a full-scale restaurant food waste treatment plant: implications of the roles beyond heavy metals and mobile genetic elements. J. Environ. Sci. 85, 17–34.

Huang, Y.H., Liu, Y., Du, P.P., Zeng, L.J., Mo, C.H., Li, Y.W., Lu, H., Cai, Q.Y., 2019. Occurrence and distribution of antibiotics and antibiotic resistant genes in water and sediments of urban rivers with black-odor water in Guangzhou, South China. Sci. Total Environ. 670, 170–180.

Jia, J.J., Guan, Y.J., Cheng, M.Q., Chen, H., He, J.F., Wang, S., Wang, Z.Z., 2018. Occurrence and distribution of antibiotics and antibiotic resistance genes in Ba River, China. Sci. Total Environ. 642, 1136–1144.

Johnson, A.C., Keller, V., Dumont, E., Sumpter, J.P., 2015. Assessing the concentrations and risks of toxicity from the antibiotics ciprofloxacin, sulfamethoxazole, trimethoprim and erythromycin in European rivers. Sci. Total Environ. 511, 747–755.

Kerrigan, J.F., Sandberg, K.D., Engstrom, D.R., LaPara, T.M., Arnold, W.A., 2018. Sedimentary record of antibiotic accumulation in Minnesota Lakes. Sci. Total Environ. 621, 970–979.

Kummerer, K., 2009. Antibiotics in the aquatic environment-a review-part I. Chemosphere 75, 417–434.

Lei, K.H., Lai, H.T., 2018. Effects of sunlight, microbial activity, and temperature on the declines of antibiotic lincomycin in freshwater and saline aquaculture pond waters and sediments. Environ. Sci. Pollut. Res. Int. 1–7.

Li, W.H., Shi, Y.L., Gao, L.H., Liu, J.M., Cai, Y.Q., 2013. Occurrence, distribution and potential affecting factors of antibiotics in sewage sludge of wastewater treatment plants in China. Sci. Total Environ. 445–446, 306–313.

Li, S., Shi, W.Z., Liu, W., Li, H.M., Zhang, W., Hu, J.R., Ke, Y.C., Sun, W.L., Ni, J.R., 2018. A duodecennial national synthesis of antibiotics in China's major rivers and seas (2005-2016). Sci. Total Environ. 615, 906–917.

Llorca, M., Rodriguez-Mozaz, S., Couillerot, O., Panigoni, K., de Gunzburg, J., Bayer, S., Czaja, R., Barcelo, D., 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.

Loke, M.L., Ingerslev, F., Halling-Sorensen, B., Tjornelund, J., 2000. Stability of tylosin A in manure containing test systems determined by high performance liquid chromatography. Chemosphere 40, 759–765.
Lu, X.M., Lu, P.Z., 2019. Distribution of antibiotic resistance genes in soil amended using Azolla imbricata and its driving mechanisms. Sci. Total Environ. 692, 422–431.
Michael, I., Hapeshi, E., Acena, J., Perez, S., Petrovic, M., Zapata, A., Barcelo, D., Malato, S., Fatta-Kassinos, D., 2013. Light-induced catalytic transformation of ofloxacin by solar Fenton in various water matrices at a pilot plant: mineralization and characterization of major intermediate products. Sci. Total Environ. 461, 39–48.
MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), 2015. Guidelines for the regulation of urban black-odor water in China. http://www.mohurd.gov.cn/wjfb/201509/W020150911050936.pdf.
MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), 2016. Notice on publishing the investigation of urban black-odor water in China. http://www.mohurd.gov.cn/wjfb/201602/t20160219_226677.html.
Onesios, K.M., Yu, J.T., Bouwer, E.J., 2009. Biodegradation and removal of pharmaceuticals and personal care products in treatment systems: a review. Biodegradation 20, 441–466.
Qian, M.G., Wu, H.Z., Wang, J.M., Zhang, H., Zhang, Z.L., Zhang, Y.Z., Lin, H., Ma, J.W., 2016. Occurrence of trace elements and antibiotics in manure-based fertilizers from the Zhejiang Province of China. Sci. Total Environ. 559, 174–181.
Rodriguez-Mozaz, S., Chamorro, S., Marti, E., Huerta, B., Gros, M., Sanchez-Melsio, A., Borrego, C.M., Barcelo, D., Balcazar, J.L., 2015. Occurrence of antibiotics and antibiotic resistance genes in hospital and urban wastewaters and their impact on the receiving river. Water Res. 69, 234–242.
Sarmah, A.K., Meyer, M.T., Boxall, A.B., 2006. A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment. Chemosphere 65, 725–759.
Sturini, M., Speltini, A., Maraschi, F., Profumo, A., Pretali, L., Fasani, E., Albini, A., 2010. Photochemical degradation of marbofloxacin and enrofloxacin in natural waters. Environ. Sci. Technol. 44, 4564–4569.
Sturini, M., Speltini, A., Maraschi, F., Pretali, L., Profumo, A., Fasani, E., Albini, A., Migliavacca, R., Nucleo, E., 2012a. Photodegradation of fluoroquinolones in surface water and antimicrobial activity of the photoproducts. Water Res. 46, 5575–5582.
Sturini, M., Speltini, A., Maraschi, F., Profumo, A., Pretali, L., Fasani, E., Albini, A., 2012b. Sunlight-induced degradation of soil-adsorbed veterinary antimicrobials marbofloxacin and enrofloxacin. Chemosphere 86, 130–137.
Wang, Z., Du, Y., Yang, C., Liu, X., Zhang, J.Q., Li, E.H., Zhang, Q., Wang, X.L., 2017. Occurrence and ecological hazard assessment of selected antibiotics in the surface waters in and around Lake Honghu, China. Sci. Total Environ. 609, 1423–1432.
Wei, W., Liu, M.Y., Zhang, W.J, Zhao, Y.Z., Guo, X.Y., Cui, Q., Huang, J.S, Yao, X.H., 2019. Studies on influencing factors of heterotrophic nitrifying bacteria treating black and odorous water bodies. AIP Publishing 2122, 020072.
Xu, W.H., Zhang, G., Zou, S.C., Li, X.D., Liu, Y.C., 2007. Determination of selected antibiotics in the Victoria Harbour and the Pearl River, South China using high-performance liquid chromatography-electrospray ionization tandem mass spectrometry. Environ. Pollut. 145, 672–679.
Xu, W.H., Zhang, G., Zou, S.C., Ling, Z.H., Wang, G.L., Yan, W., 2009. A preliminary investigation on the occurrence and distribution of antibiotics in the Yellow River and its tributaries, China. Water Environ. Res. 81, 248–254.
Xu, Z.A., Li, T., Bi, J., Wang, C., 2018. Spatiotemporal heterogeneity of antibiotic pollution and ecological risk assessment in Taihu Lake Basin, China. Sci. Total Environ. 643, 12–20.
Yang, J.F., Ying, G.G., Zhao, J.L., Tao, R., Su, H.C., Liu, Y.S., 2011. Spatial and seasonal trends of selected antibiotics in Pearl Rivers, South China. J. Environ. Sci. Health B 46, 272–280.
Yang, Y.W., Liu, Z.X., Xing, S.C., Liao, X.D., 2019. The correlation between antibiotic resistance gene abundance and microbial community resistance in pig farm wastewater and surrounding rivers. Ecotoxicol. Environ. Saf. 182, 109452.
Yao, L.L., Wang, Y.X., Tong, L., Li, Y.G., Deng, Y.M., Guo, W., Gan, Y.Q., 2015. Seasonal variation of antibiotics concentration in the aquatic environment: a case study at Jianghan Plain, central China. Sci. Total Environ. 527–528, 56–64.
Zhang, Q.Q., Ying, G.G., Pan, C.G., Liu, Y.S., Zhao, J.L., 2015. Comprehensive evaluation of antibiotics emission and fate in the river basins of China: source analysis, multimedia modeling, and linkage to bacterial resistance. Environ. Sci. Technol. 49, 6772–6782.
Zhang, M., Liu, Y.S., Zhao, J.L., Liu, W.R., He, L.Y., Zhang, J.N., Chen, J., He, L.K., Zhang, Q.Q., Ying, G.G., 2018. Occurrence, fate and mass loadings of antibiotics in two swine wastewater treatment systems. Sci. Total Environ. 639, 1421–1431.
Zhou, L.J., Ying, G.G., Zhao, J.L., Yang, J.F., Wang, L., Yang, B., Liu, S., 2011. Trends in the occurrence of human and veterinary antibiotics in the sediments of the Yellow River, Hai River and Liao River in northern China. Environ. Pollut. 159, 1877–1885.
Zhou, L.J., Ying, G.G., Liu, S., Zhao, J.L., Chen, F., Zhang, R.Q., Peng, F.Q., Zhang, Q.Q., 2012. Simultaneous determination of human and veterinary antibiotics in various environmental matrices by rapid resolution liquid chromatography-electrospray ionization tandem mass spectrometry. J. Chromatogr., A 1244, 123–138.
Zhou, L.J., Ying, G.G., Liu, S., Zhao, J.L., Yang, B., Chen, Z.F., Lai, H.J., 2013. Occurrence and fate of eleven classes of antibiotics in two typical wastewater treatment plants in South China. Sci. Total Environ. 452–453, 365–376.
Zhou, Y.Q., Meng, J., Zhang, M., Chen, S.Q., He, B., Zhao, H., Li, Q.F., Zhang, S., Wang, T.Y., 2019. Which type of pollutants need to be controlled with priority in wastewater treatment plants: traditional or emerging pollutants? Environ. Int. 131, 104982.