

 方知库
Eco-Environmental
Knowledge Web

环境科学

ENVIRONMENTAL SCIENCE

ISSN 0250-3301 CODEN HCKHDV
HUANJING KEXUE

- 主办 中国科学院生态环境研究中心
- 出版 科学出版社



2019

Vol.40 No.3
第40卷 第3期

目次

2014~2017北京市气象条件和人为排放变化对空气质量改善的贡献评估.....尹晓梅,李梓铭,熊亚军,乔林,邱雨露,孙兆彬,寇星霞(1011)

利用多元线性回归方法评估气象条件和控制措施对APEC期间北京空气质量的影响.....李颖若,汪君霞,韩婷婷,王焱,何迪,权维俊,马志强(1024)

京津冀郊区站点秋冬季大气PM_{2.5}来源解析.....王彤,华阳,许庆成,王书肖(1035)

四川省典型工业行业PM_{2.5}成分谱分析.....冯小琼,陈军辉,熊文朋,梅林德,徐雪梅,尹寒梅,范武波,姜涛,钱骏,叶宏(1043)

典型物流城市2016年冬季2次污染过程PM_{2.5}污染特征及来源解析.....赵雪艳,杨文,王静,刘盈盈,白雯宇,徐艳萍,王歆华,白志鹏(1052)

沈阳市采暖期与非采暖期空气PM_{2.5}污染特征及来源分析.....张显,田莎莎,刘盈盈,赵雪艳,余浩,张辉,陈莉,王歆华(1062)

新乡冬季PM_{2.5}中金属元素与水溶性离子年际变化及其来源解析.....闫广轩,雷豪杰,张靖雯,唐明双,张佳羽,曹治国,李云蓓,王跃思,樊静,李虎(1071)

烟台市环境受体PM_{2.5}四季污染特征与来源解析.....刘童,王晓军,陈倩,温杰,黄渤,朱红霞,田瑛泽,冯银厂(1082)

常州市冬季PM_{2.5}中类腐殖质昼夜特征分析.....顾远,李清,黄雯倩,赵竹子,马帅帅,叶招莲(1091)

西北某电子垃圾拆解厂室内外重金属污染特征及暴露风险.....曹红梅,赵留元,穆熙,李尧捷,毛潇萱,黄韬,马建民,高宏(1101)

京津冀一次污染过程的星地同步动态监测分析.....邱昀,李令军,姜磊,王新辉,赵文慧,张立坤,鹿海峰(1111)

中国城市O₃浓度时空变化特征及驱动因素.....黄小刚,赵景波,曹军骥,宋永永(1120)

基于卫星和地面观测的2013年以来我国臭氧时空分布及变化特征.....张倩倩,张兴赢(1132)

舟山市臭氧污染分布特征及来源解析.....王俏丽,董敏丽,李素静,吴成志,王刚,陈必新,李伟,高翔,叶荣民(1143)

中国建筑涂料使用VOCs排放因子及排放清单的建立.....高美平,邵霞,聂磊,王海林,安小栓(1152)

异戊二烯和甲苯二次有机硫踪物的臭氧非均相氧化.....黄亚娟,曹罡,朱荣淑,欧阳峰(1163)

兰州市农牧业源氨排放清单及其时空分布特征.....栗世学,郭文凯,何昕,朱玉凡,陈强(1172)

成都次降水稳定氢氧同位素特征及水汽来源分析.....胡月,刘国东,孟玉川,张文江,夏成城(1179)

基于TBL模型的闽江口围垦养虾塘水-大气界面CO₂扩散通量估算.....张逸飞,杨平,赵光辉,李玲,谭立山,全川(1188)

渤海和北黄海有色溶解有机物(CDOM)的分布特征和季节变化.....刘兆冰,梁文健,秦礼萍,唐建辉(1198)

思林水库荧光溶解性有机质的特征、来源及其转化动力学.....劳心宇,原杰,刘瑜, Khan M. G. Mostofa(1209)

厦门湾海滩微塑料污染特征.....刘启明,梁海涛,锡桂莉,胡欣,葛健(1217)

高分辨率监测下的漓江省里断面生物地球化学特征分析.....王奇岗,肖琼,赵海娟,王健力,郭永丽,张清华(1222)

鲜水河断裂带拉花盆地地下水化学特征及控制因素.....何锦,张幼宽,赵雨晴,韩双宝,刘元晴,张涛(1236)

成都市锦江表层水和沉积物中有机磷酸酯的污染特征.....吴迪,印红玲,李世平,王增武,邓旭,罗怡,罗林(1245)

丹江口库区表层浮游细菌群落组成与PICRUS1功能预测分析.....张菲,田伟,孙峰,陈彦,丁传雨,庞发虎,姚伦广,李玉英,陈兆进(1252)

蓝藻水华对太湖水柱反硝化作用的影响.....刘志迎,许海,詹旭,朱广伟,秦伯强,张运林(1261)

基于微生物生物完整性指数的城市河道生态系统健康评价.....苏瑛,许育新,安文浩,王云龙,何振超,楼颖雯,沈阿林(1270)

生物炭添加对湿地植物菖蒲根系通气组织和根系泌氧的影响.....黄磊,梁根坤,梁岩,罗星,陈玉成(1280)

城市不同材料屋面径流的污染负荷特性.....何湖滨,陈诚,林育青,严晗璐,董建玮,陈求稳(1287)

BiOCl-(NH₄)₃PW₁₂O₄₀复合光催化剂制备及其光催化降解污染物机制.....张文海,吉庆华,兰华春,李静(1295)

微米铁复合生物碳源对地下水中1,2-二氯乙烷的高效去除.....吴乃瑾,宋云,魏文侠,王海见,孙仲平(1302)

鸟粪石天然沸石复合材料对水中铅离子的去除.....邓曼君,王学江,成雪君,景焕平,赵建夫(1310)

Ca/Mg负载改性渣渣生物炭对水中磷的吸附特性.....易蔓,李婷婷,李海红,黄巧,杨金娥,陈玉成,杨志敏(1318)

两种生物炭的制备及其对水溶液中四环素去除的影响因素.....程扬,沈启斌,刘子丹,杨小莹,张太平,廖志钟(1328)

静止和水动力扰动状态下铅改性沸石添加对河道底泥磷迁移转化的影响.....俞阳,林建伟,詹艳慧,何思琪,吴小龙,王艳,赵钰颖,林莹,刘鹏茜(1337)

4种磺胺类药物及乙酰化代谢物在污水处理厂的去除及机制.....王大鹏,张烟,颜昌宙(1347)

以膜分离为主的物化法对城市污水中污染因子的去除特性分析.....徐婷,李勇,朱怡嘉,薛梦婷,汤同欢(1353)

进水氨氮浓度对生物除磷颗粒系统的影响.....李冬,曹美忠,郭跃洲,梅宁,李帅,张杰(1360)

除磷亚硝化颗粒工艺启动及性能恢复.....李海玲,李冬,张杰,刘博(1367)

CAST工艺高温短程硝化的实现及其除磷性能.....马娟,杨蕊春,俞小军,周猛,陈永志(1375)

不同曝气量和好氧时间下SPNDPR系统处理低C/N城市污水的脱氮除磷性能.....袁梦飞,于德爽,巩秀珍,王晓霞,陈光辉,杜世明,甄建园(1382)

ABR除碳-亚硝化耦合厌氧氨氧化处理城市污水.....李田,曹家炜,谢凤莲,沈耀良,吴鹏,宋吟玲(1390)

室温低氨氮基质单级自养脱氮颗粒污泥启动效能与污泥特性.....谢璐琳,王建芳,钱飞跃,张泽宇,沈耀良,齐泽坤(1396)

不同种泥的厌氧氨氧化反应器的启动及动力学特征.....任君怡,陈林艺,李慧春,秦玉洁,姜雁,王桐屿,周少奇(1405)

降温过程中生物膜CANON反应器的运行特征.....付昆明,廖敏辉,周厚田,付巢,姜婍,仇付国,曹秀芳(1412)

IEM-UF同步分离反硝化系统脱氮特性及种群结构分析.....刘子奇,张岩,马翔山,张博康,曹孟京,陈昌明(1419)

温度对硝化杆菌(Nitrobacter)活性动力学影响.....于雪,孙洪伟,李维维,祁国平,马娟,陈永志,吕心涛(1426)

零价铁和微波预处理组合强化污泥厌氧消化.....牛雨彤,刘吉宝,马爽,李亚明,解立平,魏源送,孟晓山(1431)

牛粪堆肥系统环境因子对抗性基因的影响.....彭磊,王科,谷月,王爱杰(1439)

环境因子对土壤微生物呼吸及其温度敏感性变化特征的影响.....张彦军,郭胜利(1446)

三峡库区典型微生物土壤呼吸及其组分对模拟酸雨的反应.....李一凡,王玉杰,王彬,王云琦(1457)

三峡库区柑橘园施肥量对土壤氮淋失及残留量的影响.....王甜,黄志霖,曾立雄,肖文发,宋文梅(1468)

长期施肥下水稻根际和非根际土壤微生物碳源利用特征.....宁赵,程爱武,唐海明,葛体达,邓扬悟,苏以荣,陈香碧(1475)

不同碳负荷梯度下稻田土壤有机碳矿化特征.....童瑶瑶,王季斐,祝贞科,邓扬悟,陈珊,葛体达,袁红朝,吴金水(1483)

桂林市仙喀斯特湿地水位梯度下不同植物群落土壤有机碳及其组分特征.....徐广平,李艳琼,沈育伊,张德楠,孙英杰,张中峰,周龙武,段春燕(1491)

缙云山4种森林植被土壤团聚体有机碳分布特征.....王富华,吕盛,黄容,高明,王子芳,徐畅(1504)

大气污染对居民健康影响研究进展.....秦耀辰,谢志祥,李阳(1512)

《环境科学》征订启事(1042) 《环境科学》征稿简则(1162) 信息(1208, 1235, 1286)

4种磺胺类药物及乙酰化代谢物在污水处理厂的去除及机制

王大鹏^{1,2}, 张娴^{1*}, 颜昌宙¹

(1. 中国科学院城市环境研究所, 城市环境与健康重点实验室, 厦门 361021; 2. 中国科学院大学, 北京 100049)

摘要: 乙酰化代谢物是磺胺类药物的重要代谢产物。为研究4种常见磺胺类药物及其乙酰化代谢物在污水厂中的去除机制, 根据污水停留时间采集厦门某A²/O型工艺污水厂不同处理单元的污水和污泥样品, 采用固相萃取-高效液相色谱串联质谱法检测目标化合物。结果显示, 8种目标物中有6种在水体中被检测出, 污泥中有5种目标物被检测出。计算总去除率及各个处理单元间的去除率, 结果表明, 磺胺二甲基嘧啶在污水厂中总去除率几乎为0, 而其他5种化合物都有不同程度的去除, 但不同目标物在各处理单元的去除率不同。利用质量平衡, 分析各物质可能的去除机制, 磺胺二甲基嘧啶可能去除机制为污泥吸附, 磺胺嘧啶、磺胺甲基嘧啶和磺胺甲噁唑可能的去除机制均为生物降解。

关键词: 磺胺类药物; 乙酰化代谢物; 去除率; 污水处理厂(WWTPs); 质量平衡

中图分类号: X703.1 文献标识码: A 文章编号: 0250-3301(2019)03-1347-06 DOI: 10.13227/j.hjkk.201804094

Removal Efficiencies and Mechanism Research on Four Sulfonamides and Their Acetyl Metabolites in a Wastewater Treatment Plant

WANG Da-peng^{1,2}, ZHANG Xian^{1*}, YAN Chang-zhou¹

(1. Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; 2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: Acetyl metabolites are the major metabolites of sulfonamides. In order to investigate the removal mechanism of four commonly used sulfonamides and their metabolites in wastewater treatment plants, sulfonamides and their corresponding acetyl metabolites in wastewater and sludge in a wastewater treatment plant equipped with A²/O in Xiamen City were sampled. Sample selection was based on the hydraulic retention time. Solid phase extraction followed by high performance liquid chromatography tandem mass spectrometry (HPLC-MS/MS) was applied to analyze the target compounds. Results showed that six out of eight of the target compounds were detected in the wastewater, while five were detected in the sludge. Based on the removal efficiencies overall and of the different compartments, the concentration of sulfamethazine was almost unchanged during wastewater treatment plant (WWTP) processes, the other sulfonamides were removed with different removal efficiencies. Removal efficiencies varied for every compartment. The potential removal pathways were analyzed based on the mass balance of the target compounds. The removal pathway of sulfamethazine was sludge adsorption, while the potential removal mechanism of sulfamerazine, sulfadiazine, and sulfamethoxazole was biodegradation.

Key words: sulfonamides; acetyl metabolites; removal efficiency; wastewater treatment plants (WWTPs); mass balance

我国是抗生素生产和使用大国, 2013年我国抗生素生产及使用量分别为24.8万t及16.2万t^[1]。磺胺类药物(sulfonamide, SAs)是一种常用的抗生素, 具有对氨基苯磺酰胺的结构, 主要用于预防和治疗细菌感染疾病^[2]。进入人体及动物体的磺胺类药物不能完全吸收, 大部分以原型及其代谢物随尿液及粪便排出体外^[3]进入污水处理厂(wastewater treatment plants, WWTPs), 污水处理厂是城市污水的重要接纳体, 但是目前的污水厂很难有效地去除磺胺类等抗生素药物^[4,5]。过量使用磺胺类药物会导致其在水环境中大量残留, 水环境中的磺胺类药物在国内外被广泛检出^[6,7], 不能完全去除的磺胺类药物随污水处理厂出水排入自然水体中^[8], 导致磺胺类药物在水生生物体内累积, 危害其健康。除此之外, 磺胺类药物的滥用可能会引起耐药性, 对

生态环境和人类造成危害^[9,10]。乙酰化代谢物是磺胺类药物的主要代谢产物^[11,12], 乙酰化代谢物在尿中溶解度低, 析出结晶后增加了对肾脏的毒性^[13]。目前国内虽然有乙酰化代谢物的相关研究, 但大多数研究者都是研究其在动物源性食品^[14-16]以及血清样品^[17]中的含量, 在环境中的含量研究目前尚处于起步阶段。

由于某些抗生素会在污泥相中吸附, 水相的去除率并不能准确地反映抗生素的去除情况, 质量平衡分析是一种有效地研究抗生素在环境中的归趋及其对环境的质量负荷的方法^[18,19]。Yan等^[20]研究

收稿日期: 2018-04-12; 修订日期: 2018-09-18

基金项目: 国际科技合作项目(2011DFB91710)

作者简介: 王大鹏(1989~), 男, 博士研究生, 主要研究方向为新兴污染物的检测与分析, E-mail: dpwang@iue.ac.cn

* 通信作者, E-mail: xzhang@iue.ac.cn

了包括磺胺类药物在内的 21 种医药活性物质在某污水处理厂中的质量平衡,发现大部分药物在污水处理厂的主要去除途径是生物降解,少部分是污泥吸附作用. 综上,研究环境中乙酰化代谢物含量,计算质量平衡,分析其与母体化合物相互转化规律及可能的降解机制,对研究这些化合物在污水处理厂中的环境行为及开展环境风险管理具有重要意义.

本文选取 4 种常见的磺胺类药物及其相应的乙酰化代谢物为研究对象,采用高效液相色谱串联质谱(HPLC-MS/MS)检测其在厦门某污水处理厂中的浓度,探讨了目标物在污水处理厂的分布规律,通过质量平衡分析,考察污水处理厂中磺胺类药物与乙酰化代谢物的转化过程及其可能的去除机制,以期为今后进一步考察磺胺类药物及其代谢物在污水及污泥中的迁移转化提供参考数据.

1 材料与方 法

1.1 仪器与试剂

高效液相色谱串联四级杆质谱仪(液相色谱, LC20-AD, 日本岛津公司; 四级杆质谱仪, 3200QTRAP, 美国 ABI 公司), 配备电喷雾离子源(ESI); Milli-Q 超纯水仪(美国 Millipore 公司).

标准品磺胺嘧啶(sulfadiazine, SD, 99%)、磺胺甲噁唑(sulfamethoxazole, SMZ, 99%)、磺胺甲基嘧啶(sulfamerazine, SM1, 99.5%)、磺胺二甲嘧啶(sulfamethazine, SM2, 99.6%)和乙酰化磺胺甲噁唑(Acetyl-sulfamethoxazole, Ac-SMZ, 99%)购自德国 Dr. Ehrenstorfer 公司, 乙酰化磺胺甲基嘧啶(*N*-acetyl sulfamerazine, Ac-SM1, 98%)、乙酰化磺胺嘧啶(*N*-acetyl sulfadiazine, Ac-SD, 97%)和乙酰化磺胺二甲嘧啶(*N*-acetyl sulfamethazine, Ac-SM2, 98%)购自加拿大 TRC 公司, 同位素标记的内标物¹³C₆磺胺嘧啶(¹³C₆-sulfadiazine, ¹³C₆-SD, 99.4%)和替代物¹³C₆磺胺甲噁唑(¹³C₆-sulfamethoxazole, ¹³C₆-SMZ, 99.7%)购自德国 Witega 公司. 本研究使用的有机试剂均为色谱纯, 甲醇购自美国 TEDIA 公司, 甲酸购自上海阿拉丁试剂公司. 本实验用的超纯水由 Milli-Q 系统提供. SAX 固相萃取小柱(500 mg, 6 mL)购自美国 Agilent 公司, Oasis HLB 固相萃取小柱(500 mg, 6 mL)购自美国 Waters 公司.

1.2 样品采集

本文选取了厦门某污水处理厂作为研究对象,其污水进水主要来自城市生活污水,总服务面积约 36 km², 服务人口半径约 20 万人, 本文选取该污水处理厂 A²/O 工艺的二期工程. A²/O 工艺是目前处理我国城市污水常见的脱氮除磷工艺, 其去除污染

物机制是利用微生物对污染物的生物降解. 该工艺处理效果稳定可靠, 运行管理较简单.

采用 4 L 的棕色玻璃瓶采集污水, 根据污水厂各个处理单元的水力停留时间, 按照污水处理过程采样, 减小不同批次的污水带来的误差. 同时采集污泥样品, 污水采样点分别为沉砂池(S1), 厌氧进水(S2)、缺氧进水(S3)、好氧进水(S4)、好氧出水(S5)、二沉池出水(S6)和紫外出水(S7). 污泥采样除了在厌氧、缺氧、好氧区(S2~S5)随污水采样之外, 同时采集剩余污泥(S8)及脱水污泥(S9), 采样时采集 3 份平行样品. 采集水样后加入硫酸调节至 pH 3.0, 低温保存带回实验室并于 48 h 内处理完. 采样时间为 2016 年 8 月. 采样点位如图 1 所示.

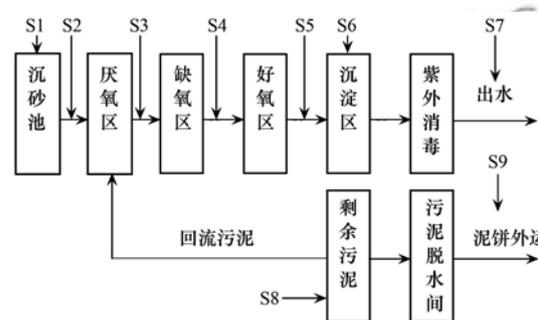


图 1 污水厂采样点位分布示意
Fig. 1 Schematic diagram of the WWTP

1.3 样品前处理及检测

样品前处理与检测方法参照笔者之前开发的方法测定, 500 mL 水样用微孔滤膜过滤后用 HLB 固相萃取小柱富集, 污泥样品用柠檬酸盐缓冲液萃取, 收集萃取液, 用 SAX 与 HLB 串联提取与富集, 使用 HPLC-MS/MS 测定样品.

1.4 质量控制和质量保证

本文采用¹³C₆-SD 作为内标, ¹³C₆-SMZ 作为替代物. 替代物在萃取前加入到污泥和污水中以监控整个分析过程, 加入内标以校正基质效应. 设置 3 份平行控制误差, 样品检测时, 每隔 10 个样品回测一次标样进行质量控制. 所有的数据都经过严格的质量控制, 通过加标测量回收率, 本文选取了 2 种浓度, 加入 20 ng·L⁻¹ 和 100 ng·L⁻¹ 混合标准溶液. 污水的回收率为 70.8% ~ 130.6%, 污泥的回收率为 88.0% ~ 129.2%. 污水检出限为 0.19 ~ 2.06 ng·L⁻¹, 污泥检出限为 0.61 ~ 2.31 ng·g⁻¹.

2 结果与讨论

2.1 目标化合物在污水处理厂污水和污泥的含量分布

采集并检测厦门市某污水处理厂中污水及污泥

中磺胺类药物及其乙酰化代谢物含量, 结果如图 2 所示, 8 种化合物在污水中检测出来 6 种, SM1 和 Ac-SD 没有被检测出. 污泥只检测出 5 种目标化合物, Ac-SMZ、SM1 及其代谢物 Ac-SM1 没有被检测出. Li 等^[21]研究了两个污水处理厂中磺胺类的浓度, SM2 和 SD 浓度均较低. 在污水进水中 Ac-SMZ 浓度最高, 为 $109.4 \text{ ng}\cdot\text{L}^{-1}$, 而在所有的污泥样品中均没有检测到该物质, 该结果和 Göbel 等^[22]的研

究一致, 该研究在污泥中加入 $100 \mu\text{g}\cdot\text{kg}^{-1}$ 含量的 Ac-SMZ, 结果导致污泥中的 SMZ 含量增加, 但却没有在污泥中检测到, 所以 Göbel 推测 Ac-SMZ 会在污泥环境中迅速转化为 SMZ. 本研究中污泥的目标化合物含量较低, Huang 等^[23]研究了污泥中几种抗生素的含量, 其中磺胺类抗生素在污泥中的含量也较低, SD、SMZ 和 SM2 平均含量分别为 8.7 、 12.35 和 $14.9 \text{ ng}\cdot\text{g}^{-1}$.

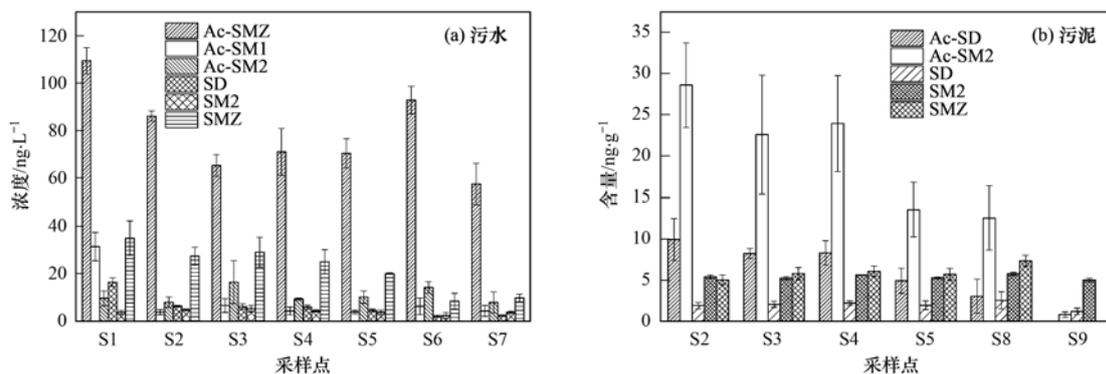


图 2 目标物在污水处理厂污水及污泥中的含量

Fig. 2 Concentrations of target compounds in the wastewater and sludge in the WWTP

由图 2 可以看出, 在厌氧进水的磺胺类抗生素及其母体的浓度明显低于进水的目标化合物浓度, 这可能是由于从厌氧开始的生化池相比于进水, 存在大量污泥, 而污泥吸附是磺胺类药物在污水处理厂的主要降解行为之一^[24,25].

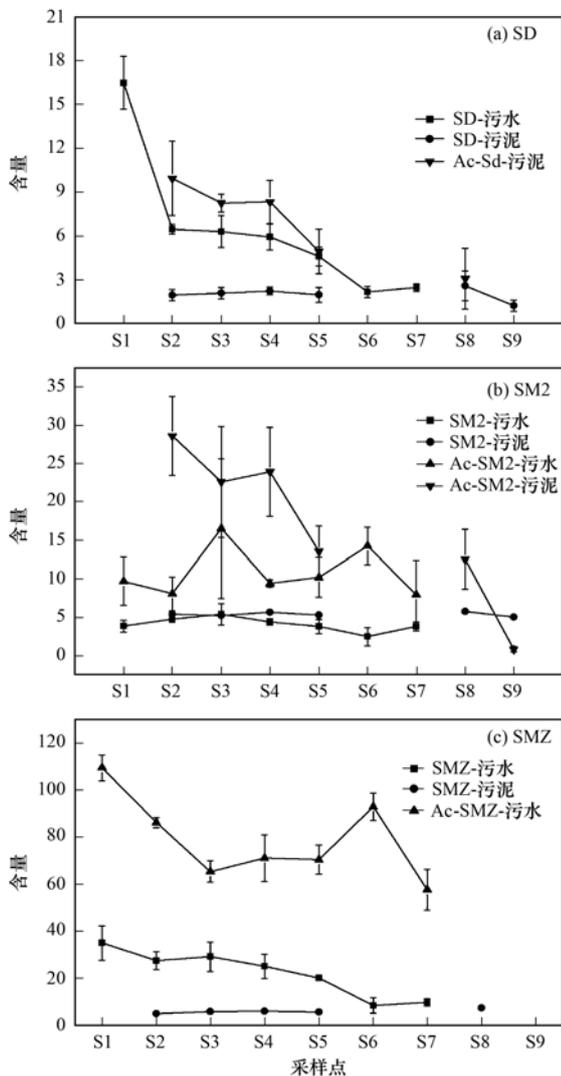
各个磺胺类药物和其相应的乙酰化代谢物在污水与污泥中的含量变化情况如图 3 所示, 其中 SM1 由于在污水和污泥中未被检出, 故没有列出, 可以看出 SD 整体随污水处理厂工艺呈下降趋势, 其中 SD 在污水, Ac-SD 在污泥下降趋势较为明显, SD 在污泥中随各个污水处理单元变化基本不明显, Ac-SD 在污水中则未检出. SD 随污水浓度降低明显, 而污泥含量基本不变, 但其相应的乙酰化代谢物并未显著提高, 可能有两种原因, 一是 SD 在污水处理过程中转化为其他代谢物, 二是 SD 在污水处理过程中产生了微生物降解, 使 SD 浓度降低. 而 SM2 在随各污水厂处理单元呈现波动的情况, 特别是 Ac-SM2 在污水和污泥中呈现此消彼长的情况, 这可能是由于 Ac-SM2 随污水处理厂各处理单元在污泥中不断吸附和解吸, 而母体化合物 SM2 在污水和污泥中随处理单元进程变化不明显. SMZ 的含量变化情况整体与 SD 类似.

2.2 目标化合物的去除率

污水及污泥在污水厂各处理单元及整个过程的去除率如图 4 和图 5 所示, 去除率的计算公式为:

$$R(\%) = [1 - (c_e/c_i)] \times 100 \quad (1)$$

式中, $R(\%)$ 代表某一处理单元的去除率, c_i 表示某一处理单元进水浓度, c_e 表示某一处理单元出水浓度. 污水中磺胺类药物及其乙酰化代谢物的去除率中(图 4), 总去除率除了 SM2 几乎不变之外, 其余 5 种均有不同程度的去除, Ac-SM1 和 SD 去除效果明显, 分别为 86.1% 和 85.2% , SMZ 也有较高的去除(71.9%). Li 等^[26]的研究发现 SD 和 SMZ 在城市污水处理厂中具有较高的去除率, 其研究香港两个污水处理厂的去除率, 其中, 一个污水厂中 SD 和 SMZ 的去除率为 72.8% 和 68.2% , 另一个污水厂 SMZ 去除率高达 95.7% , 而 SD 未检出. 而对于不同的处理单元, 污水在初沉池去除效果明显, 这可能是由于进入生化池段, 存在大量污泥, 目标物在污泥中发生快速吸附作用. 二沉池阶段的去除率, 磺胺类母体化合物为正去除, 乙酰化代谢物为负去除, 推测该阶段的母体化合物转化为乙酰化代谢物. 而在紫外阶段则和二沉池情况相反, 母体化合物出现负去除, 这可能是化合物结合体结构在紫外条件下发生改变形成自由体, 使得基质中的物质间的相互作用发生改变, 从而导致更多的目标物被检出^[27]. 而对于污泥中目标化合物的去除率(图 5), 总体来说, Ac-SD 和 SMZ 的去除率都是 100% , Ac-SM2 也有较高的去除率, 高达 97.2% , SM2 去除效果最差, 为 7.3% . 在各处理单元中, 脱水造成的目标物去除率是最高的, 其次是在好氧区.



污泥中物质的单位: $\text{ng}\cdot\text{g}^{-1}$; 污水中物质的单位: $\text{ng}\cdot\text{L}^{-1}$

图3 母体化合物与乙酰化代谢物在污水过程的转化

Fig. 3 Transformation of parent compounds and their acetyl metabolites during WWTP treatment

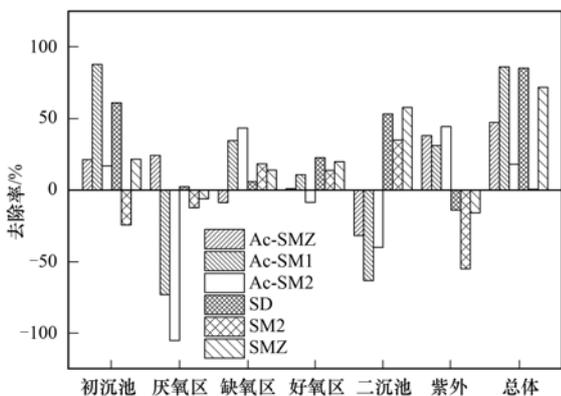


图4 污水处理厂污水中磺胺类及乙酰化代谢物在各个处理单元及总体的去除率

Fig. 4 Removal efficiency of target compounds in wastewater for different compartments and overall process in the WWTP

2.3 目标物在污水处理厂可能的去除机制
通过质量平衡分析可以更好地了解磺胺类药物

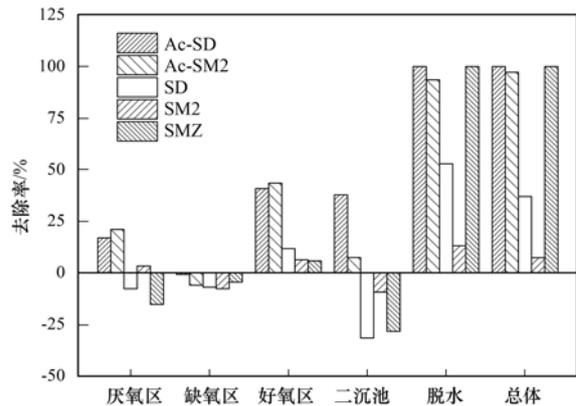


图5 污水处理厂污泥中磺胺类及乙酰化代谢物在各个处理单元及总体的去除率

Fig. 5 Removal efficiency of target compounds in sludge of different compartments and in overall process in the WWTP

及其代谢物在污水处理厂中可能的去除机制. 质量平衡分析通过日质量流量与损失计算, 按以下公式计算:

$$M_i = Q_w \times C_i \times 10^{-6} \quad (2)$$

$$M_e = Q_w \times C_e \times 10^{-6} \quad (3)$$

$$M_s = Q_s \times C_s \times 10^{-3} \quad (4)$$

$$M_l = M_i - M_e - M_s \quad (5)$$

$$M_{l\%} = M_l / M_i \quad (6)$$

式中, M_i 、 M_e 、 M_s 分别代表进水、出水、污泥的日质量流量 ($\text{g}\cdot\text{d}^{-1}$), C_i 、 C_e 、 C_s 分别代表进水 ($\text{ng}\cdot\text{L}^{-1}$)、出水 ($\text{ng}\cdot\text{L}^{-1}$) 和剩余污泥 ($\text{ng}\cdot\text{g}^{-1}$) 的目标物含量, Q_w 和 Q_s 分别代表污水和污泥的日流量, 采样期间平均污水和剩余污泥日流量分别为 $3\text{万m}^3\cdot\text{d}^{-1}$ 和 $3.9\text{t}\cdot\text{d}^{-1}$. M_l 和 $M_{l\%}$ 分别为质量流量损失和质量流量损失率. 计算目标化合物的质量流量及损失, 结果如表1所示.

由表1可以得知, 磺胺类化合物的污水质量流量高于污泥质量流量, 这可能是由于磺胺类药物的辛醇/水分配系数 (K_{ow}) 较低, 水溶性较强, 更容易溶解到水相当中, 而污泥相的吸附较差. 此外, 除了SM2之外, 目标物均出现一定程度的质量损失, 即在污水处理过程中产生了生物降解或转化. 例如SMZ及其乙酰化代谢物Ac-SMZ在污水处理过程中的总体质量损失分别为69.2%和47.3%, 说明SMZ在污水厂中的主要去除机制是生物降解, 这与前文通过图3的推测一致, 而SM2及其乙酰化代谢物Ac-SM2在污水处理过程中的总体质量损失分别为-19.1%和1.2%, Ac-SM2的质量损失接近零, 而SM2的质量损失出现负值, 这说明SM2在污水处理过程中的去除机制基本没有生物降解, 同时, SM2和Ac-SM2的污泥质量流量占进水质量流量的19.1%和16.9%, 而SD和SMZ的这一占比分别为

2.0% 和 2.8%, 其余化合物则为零, 这说明 SM2 在污水处理过程的可能去除机制为污泥吸附, 而出现负值的原因可能是其他代谢物转化为母体化合物. SD 与 SM1 的去除机制则与 SMZ 一致, 在本研究中

主要为生物降解. 这与高俊红等^[28]的研究结果相似, 其研究了兰州污水厂中 9 种磺胺类分布特征, 并通过质量平衡分析, 发现生物转化或降解是其主要的去除机制.

表 1 目标物的质量流量及质量平衡

Table 1 Mass load and mass balance of target compounds

化合物	$M_i/g \cdot d^{-1}$	$M_e/g \cdot d^{-1}$	$M_s/g \cdot d^{-1}$	$M_l/g \cdot d^{-1}$	$M_{loss}/\%$
Ac-SMZ	3.282	1.728	0	1.554	47.3
Ac-SM1	0.944	0.131	0	0.813	86.1
Ac-SM2	0.290	0.238	0.049	0.004	1.2
SD	0.495	0.073	0.010	0.411	83.2
SM2	0.115	0.114	0.022	-0.022	-19.1
SMZ	1.05	0.295	0.029	0.726	69.2

3 结论

(1) 使用 HPLC-MS/MS 检测厦门某 A²/O 型污水厂中的 4 种磺胺类及其相应的乙酰化代谢物的浓度, 8 种目标物中有 6 种在水体中被检测出, 污泥中有 5 种目标物被检测出, 与其他污水处理厂相比处于一个正常水平, Ac-SMZ 在污泥中会迅速转化为 SMZ.

(2) 磺胺类及其相应的乙酰化代谢物在污水处理厂各处理单元的去除率, 除了 SM2 总去除率基本为 0 之外, 其余 5 种化合物均有不同程度的去除.

(3) SM2 在污水处理厂中的主要去除机制是污泥吸附, SD、SM1、SMZ 在污水处理厂中的主要去除机制是生物降解.

参考文献:

[1] Zhang Q Q, Ying G G, Pan C G, *et al.* Comprehensive evaluation of antibiotics emission and fate in the river basins of China: source analysis, multimedia modeling, and linkage to bacterial resistance[J]. *Environmental Science & Technology*, 2015, **49**(11): 6772-6782.

[2] 金磊, 姜蕾, 韩琪, 等. 华东地区某水源水中 13 种磺胺类抗生素的分布特征及人体健康风险评估[J]. *环境科学*, 2016, **37**(7): 2515-2521.

Jin L, Jiang L, Han Q, *et al.* Distribution characteristics and health risk assessment of thirteen sulfonamides antibiotics in a drinking water source in East China[J]. *Environmental Science*, 2016, **37**(7): 2515-2521.

[3] Lertpaitoonpan W, Ong S K, Moorman T B. Effect of organic carbon and pH on soil sorption of sulfamethazine [J]. *Chemosphere*, 2009, **76**(4): 558-564.

[4] 甘秀梅, 严清, 高旭, 等. 典型抗生素在中国西南地区某污水处理厂中的行为和归趋[J]. *环境科学*, 2014, **35**(5): 1817-1823.

Gan X M, Yan Q, Gao X, *et al.* Occurrence and fate of typical antibiotics in a wastewater treatment plant in southwest China [J]. *Environmental Science*, 2014, **35**(5): 1817-1823.

[5] 柴玉峰, 张玉秀, 陈梅雪, 等. 冀西北典型北方小城镇污水处理厂中抗生素的分布和去除[J]. *环境科学*, 2018, **39**(6): 2724-2731.

Chai Y F, Zhang Y X, Chen M X, *et al.* Distribution and

treatment of antibiotics in typical WWTPs in small towns in China [J]. *Environmental Science*, 2018, **39**(6): 2724-2731.

[6] 张晓娇, 柏杨巍, 张远, 等. 辽河流域地表水中典型抗生素污染特征及生态风险评估[J]. *环境科学*, 2017, **38**(11): 4553-4561.

Zhang X J, Bai Y W, Zhang Y, *et al.* Occurrence, distribution, and ecological risk of antibiotics in surface water in the Liaohe river basin, China[J]. *Environmental Science*, 2017, **38**(11): 4553-4561.

[7] Hossain A, Nakamichi S, Habibullah-Al-Mamun M, *et al.* Occurrence and ecological risk of pharmaceuticals in river surface water of Bangladesh[J]. *Environmental Research*, 2018, **165**: 258-266.

[8] Sun Q, Lv M, Hu A Y, *et al.* Seasonal variation in the occurrence and removal of pharmaceuticals and personal care products in a wastewater treatment plant in Xiamen, China[J]. *Journal of Hazardous Materials*, 2014, **277**: 69-75.

[9] Martinez J L. Environmental pollution by antibiotics and by antibiotic resistance determinants[J]. *Environmental Pollution*, 2009, **157**(11): 2893-2902.

[10] Xu J, Xu Y, Wang H M, *et al.* Occurrence of antibiotics and antibiotic resistance genes in a sewage treatment plant and its effluent-receiving river[J]. *Chemosphere*, 2015, **119**: 1379-1385.

[11] Zonaras V, Tyrpenou A, Alexis M, *et al.* Determination of sulfadiazine, trimethoprim, and N⁴-acetyl-sulfadiazine in fish muscle plus skin by Liquid Chromatography-Mass Spectrometry. Withdrawal-time calculation after in-feed administration in gilthead sea bream (*Sparus aurata* L.) fed two different diets [J]. *Journal of Veterinary Pharmacology and Therapeutics*, 2016, **39**(5): 504-513.

[12] Andriamalala A, Vieublé-Gonod L, Dumény V, *et al.* Fate of sulfamethoxazole, its main metabolite N-ac-sulfamethoxazole and ciprofloxacin in agricultural soils amended or not by organic waste products[J]. *Chemosphere*, 2018, **191**: 607-615.

[13] Kishida K, Furusawa N. Application of shielded column liquid chromatography for determination of sulfamonomethoxine, sulfadimethoxine, and their N₄-acetyl metabolites in milk [J]. *Journal of Chromatography A*, 2004, **1028**(1): 175-177.

[14] 刘思思, 杜鹃, 陈景文, 等. 加速溶剂萃取-高效液相色谱-串联质谱联用测定莱州湾海水养殖区野生鱼肌肉中 19 种抗生素及 2 种磺胺代谢产物残留[J]. *色谱*, 2014, **32**(12): 1320-1325.

Liu S S, Du J, Chen J W, *et al.* Determination of 19 antibiotic and 2 sulfonamide metabolite residues in wild fish muscle in

- mariculture areas of Laizhou Bay using accelerated solvent extraction and high performance liquid chromatography-tandem mass spectrometry [J]. Chinese Journal of Chromatography, 2014, **32**(12): 1320-1325.
- [15] Meng Z, Shi Z H, Liang S X, *et al.* Residues investigation of fluoroquinolones and sulphonamides and their metabolites in bovine milk by quantification and confirmation using ultra-performance liquid chromatography-tandem mass spectrometry [J]. Food Chemistry, 2015, **174**: 597-605.
- [16] Li H, Sun H W, Zhang J X, *et al.* Highly sensitive and simultaneous determination of sixteen sulphonamide antibiotics, four acetyled metabolites and trimethoprim in meat by rapid resolution liquid chromatography-tandem mass spectrometry [J]. Food Control, 2013, **31**(2): 359-365.
- [17] Zhang Y, Zhou W E, Li S H, *et al.* A simple, accurate, time-saving and green method for the determination of 15 sulfonamides and metabolites in serum samples by ultra-high performance supercritical fluid chromatography [J]. Journal of Chromatography A, 2016, **1432**: 132-139.
- [18] Ashfaq M, Li Y, Wang Y W, *et al.* 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 [J]. Water Research, 2017, **123**: 655-667.
- [19] Petrie B, McAdam E J, Lester J N, *et al.* Obtaining process mass balances of pharmaceuticals and triclosan to determine their fate during wastewater treatment [J]. Science of the Total Environment, 2014, **497-498**: 553-560.
- [20] Yan Q, Gao X, Huang L, *et al.* Occurrence and fate of pharmaceutically active compounds in the largest municipal wastewater treatment plant in Southwest China: mass balance analysis and consumption back-calculated model [J]. Chemosphere, 2014, **99**: 160-170.
- [21] Li J N, Cheng W X, Xu L K, *et al.* Occurrence and removal of antibiotics and the corresponding resistance genes in wastewater treatment plants: effluents' influence to downstream water environment [J]. Environmental Science and Pollution Research, 2016, **23**(7): 6826-6835.
- [22] Göbel A, Thomsen A, McArdell C S, *et al.* Occurrence and sorption behavior of sulfonamides, macrolides, and trimethoprim in activated sludge treatment [J]. Environmental Science & Technology, 2005, **39**(11): 3981-3989.
- [23] Huang Y J, Cheng M M, Li W H, *et al.* Simultaneous extraction of four classes of antibiotics in soil, manure and sewage sludge and analysis by liquid chromatography-tandem mass spectrometry with the isotope-labelled internal standard method [J]. Analytical Methods, 2013, **5**(15): 3721-3731.
- [24] Yang S F, Lin C F, Lin A Y C, *et al.* Sorption and biodegradation of sulfonamide antibiotics by activated sludge: experimental assessment using batch data obtained under aerobic conditions [J]. Water Research, 2011, **45**(11): 3389-3397.
- [25] García Galón M J, Díaz-Cruz M S, Barceló D. Removal of sulfonamide antibiotics upon conventional activated sludge and advanced membrane bioreactor treatment [J]. Analytical and Bioanalytical Chemistry, 2012, **404**(5): 1505-1515.
- [26] Li B, Zhang T, Xu Z Y, *et al.* Rapid analysis of 21 antibiotics of multiple classes in municipal wastewater using ultra performance liquid chromatography-tandem mass spectrometry [J]. Analytica Chimica Acta, 2009, **645**(1-2): 64-72.
- [27] 周海东, 黄霞, 文湘华. 城市污水中有关新型微污染物 PPCPs 归趋研究的进展 [J]. 环境工程学报, 2007, **1**(12): 1-9.
- Zhou H D, Huang X, Wen X H. Progress of the studies on occurrence and fate of new emerging micro-pollutants-PPCPs in municipal wastewaters [J]. Chinese Journal of Environmental Engineering, 2007, **1**(12): 1-9.
- [28] 高俊红, 王兆炜, 张涵瑜, 等. 兰州市污水处理厂中典型抗生素的污染特征研究 [J]. 环境科学学报, 2016, **36**(10): 3765-3773.
- Gao J H, Wang Z W, Zhang H Y, *et al.* Occurrence and the fate of typical antibiotics in sewage treatment plants in Lanzhou [J]. Acta Scientiae Circumstantiae, 2016, **36**(10): 3765-3773.

CONTENTS

Contribution Assessment of Meteorology Conditions and Emission Change for Air Quality Improvement in Beijing During 2014-2017	YIN Xiao-mei, LI Zi-ming, XIONG Ya-jun, <i>et al.</i>	(1011)
Using Multiple Linear Regression Method to Evaluate the Impact of Meteorological Conditions and Control Measures on Air Quality in Beijing During APEC 2014	LI Ying-roo, WANG Jun-xia, HAN Ting-ling, <i>et al.</i>	(1024)
Source Apportionment of PM _{2.5} in Suburban Area of Beijing-Tianjin-Hebei Region in Autumn and Winter	WANG Tong, HUA Yang, XU Qing-cheng, <i>et al.</i>	(1035)
Fine Particulate Matter Source Profile of Typical Industries in Sichuan Province	FENG Xiao-qiong, CHEN Jun-hui, XIONG Wen-peng, <i>et al.</i>	(1043)
Source Apportionment and Pollution Characteristics of PM _{2.5} During the Two Heavy Pollution Episodes in the Winter of 2016 in a Typical Logistics City	ZHAO Xue-yan, YANG Wen, WANG Jing, <i>et al.</i>	(1052)
Pollution Characteristics and Source Apportionment of PM _{2.5} in Heating and Non-heating Periods in Shenyang	ZHANG Xian, TIAN Sha-sha, LIU Ying-ying, <i>et al.</i>	(1062)
Interannual Variation of Metal Elements and Water-Soluble Ions in PM _{2.5} During Wintertime in Xinxiang and Their Source Apportionment	YAN Guang-xuan, LEI Hao-jie, ZHANG Jing-wen, <i>et al.</i>	(1071)
Pollution Characteristics and Source Apportionment of Ambient PM _{2.5} During Four Seasons in Yantai City	LIU Tong, WANG Xiao-jun, CHEN Qian, <i>et al.</i>	(1082)
Day-night Characteristics of Humic-like Substances in PM _{2.5} During Winter in Changzhou	GU Yuan, LI Qing, HUANG Wen-qian, <i>et al.</i>	(1091)
Pollution Characteristics and Occupational Exposure Risk of Heavy Metals in Indoor and Outdoor Ambient Particles at a Scaled Electronic Waste Dismantling Plant, Northwest China	CAO Hong-mei, ZHAO Liu-yuan, MU Xi, <i>et al.</i>	(1101)
Analysis of a Pollution Process in the Beijing-Tianjin-Hebei Region Based on Satellite and Surface Observations	QIU Yun, LI Ling-jun, JIANG Lei, <i>et al.</i>	(1111)
Spatial-temporal Variation of Ozone Concentration and Its Driving Factors in China	HUANG Xiao-gang, ZHAO Jing-bo, CAO Jun-ji, <i>et al.</i>	(1120)
Ozone Spatial-temporal Distribution and Trend over China Since 2013: Insight from Satellite and Surface Observation	ZHANG Qian-qian, ZHANG Xing-ying	(1132)
Characteristics of Ozone Pollution Distribution and Source Apportionment in Zhoushan	WANG Qiao-li, DONG Min-li, LI Su-jing, <i>et al.</i>	(1143)
Establishment of VOCs Emissions Factor and Emissions Inventory from Using of Architectural Coatings in China	GAO Mei-ping, SHAO Xia, NIE Lei, <i>et al.</i>	(1152)
Heterogeneous Oxidation of Secondary Organic Tracers of Isoprene and Toluene by Ozone	HUANG Ya-juan, CAO Gang, ZHU Rong-shu, <i>et al.</i>	(1163)
Inventory and Spatiotemporal Distribution of Ammonia Emission from Agriculture and Animal Husbandry in Lanzhou City	LI Shi-xue, GUO Wen-kai, HE Xin, <i>et al.</i>	(1172)
Analysis of Stable Hydrogen and Oxygen Isotope Characteristics and Vapor Sources of Event-based Precipitation in Chengdu	HU Yue, LIU Guo-dong, MENG Yu-chuan, <i>et al.</i>	(1179)
Diffusive CO ₂ Flux Across the Water-air Interface of Reclaimed Shrimp Ponds in the Minjiang River Estuary Based on the TBL Model	ZHANG Yi-fei, YANG Ping, ZHAO Guang-hui, <i>et al.</i>	(1188)
Distribution and Seasonal Variations of Chromophoric Dissolved Organic Matter (CDOM) in the Bohai Sea and the North Yellow Sea	LIU Zhao-bing, LIANG Wen-jian, QIN Li-ping, <i>et al.</i>	(1198)
Sources, Characteristics and Transformation Dynamics of Fluorescent Dissolved Organic Matter in the Silin Reservoir	LAO Xin-yu, YUAN Jie, LIU Yu, <i>et al.</i>	(1209)
Microplastic Pollution of the Beaches in Xiamen Bay, China	LIU Qi-ming, LIANG Hai-tao, XI Gui-li, <i>et al.</i>	(1217)
Biogeochemical Characteristics in Shengli Site of Lijiang River Under the High Resolution Monitoring	WANG Qi-gang, XIAO Qiong, ZHAO Hai-juan, <i>et al.</i>	(1222)
Hydrochemical Characteristics and Possible Controls of Groundwater in the Xialatuo Basin Section of the Xianshui River	HE Jin, ZHANG You-kuan, ZHAO Yu-qing, <i>et al.</i>	(1236)
Pollution Characteristics of OPEs in the Surface Water and Sediment of the Jinjiang River in Chengdu City	WU Di, YIN Hong-ling, LI Shi-ping, <i>et al.</i>	(1245)
Community Structure and Predictive Functional Analysis of Surface Water Bacterioplankton in the Danjiangkou Reservoir	ZHANG Fei, TIAN Wei, SUN Feng, <i>et al.</i>	(1252)
Influence of Cyanobacterial Blooms on Denitrification Rate in Shallow Lake Taihu, China	LIU Zhi-ying, XU Hai, ZHAN Xu, <i>et al.</i>	(1261)
Assessment of Ecosystem Health of an Urban River Based on the Microbe Index of Biotic Integrity (M-IBI)	SU Yao, XU Yu-xin, AN Wen-hao, <i>et al.</i>	(1270)
Influences of Biochar Application on Root Aerenchyma and Radial Oxygen Loss of <i>Acorus calamus</i> in Relation to Subsurface Flow in a Constructed Wetland	HUANG Lei, LIANG Yin-kun, LIANG Yan, <i>et al.</i>	(1280)
Pollution Load Characteristics of Runoff from Urban Roofs of Different Materials	HE Hu-bin, CHEN Cheng, LIN Yu-qing, <i>et al.</i>	(1287)
Preparation of BiOCl-(NH ₄) ₃ PW ₁₂ O ₄₀ Photocatalyst and a Mechanism for Photocatalytic Degradation of Organic Pollutants	ZHANG Wen-hai, JI Qing-hua, LAN Hua-chun, <i>et al.</i>	(1295)
High Efficiency Removal of 1,2-Dichloroethane from Groundwater by Microscale Zero-valent Iron Combined with Biological Carbon Source	WU Nai-jin, SONG Yun, WEI Wen-xia, <i>et al.</i>	(1302)
Removal of Lead Ions from Water by Struvite Natural Zeolite Composite	DEND Man-jun, WANG Xue-jiang, CHENG Xue-jun, <i>et al.</i>	(1310)
Characteristics of Phosphorus Adsorption in Aqueous Solution By Ca/Mg-Loaded Biogas Residue Biochar	YI Man, LI Ting-ting, LI Hai-hong, <i>et al.</i>	(1318)
Preparation of Two Kinds of Biochar and the Factors Influencing Tetracycline Removal from Aqueous Solution	CHENG Yang, SHEN Qi-bin, LIU Zi-dan, <i>et al.</i>	(1328)
Effect of Zirconium-Modified Zeolite Addition on Migration and Transformation of Phosphorus in River Sediments Under Static and Hydrodynamic Disturbance Conditions	YU Yang, LIN Jian-wei, ZHAN Yan-hui, <i>et al.</i>	(1337)
Removal Efficiencies and Mechanism Research on Four Sulfonamides and Their Acetyl Metabolites in a Wastewater Treatment Plant	WANG Da-peng, ZHANG Xian, YAN Chang-zhou	(1347)
Assessing Performance of Pollutant Removal from Municipal Wastewater by Physical and Chemical Methods Based on Membranes	XU Ting, LI Yong, ZHU Yi-jia, <i>et al.</i>	(1353)
Effect of Influent Ammonia Concentration on a Biological Phosphorus Removal Granules System	LI Dong, CAO Mei-zhong, GUO Yue-zhou, <i>et al.</i>	(1360)
Start-up and Performance Recovery of Granular Sludge for Phosphorus Removal and Nitrification	LI Hai-ling, LI Dong, ZHANG Jie, <i>et al.</i>	(1367)
Realization of Short-cut Nitrification in a CAST Process at High Temperature and Its Phosphorus Removal Performance	MA Juan, YANG Rui-chun, YU Xiao-jun, <i>et al.</i>	(1375)
Nitrogen and Phosphorus Removal from Low C/N Municipal Wastewater Treated by a SPNDR System with Different Aeration and Aerobic Times	YUAN Meng-fei, YU De-shuang, GONG Xiu-zhen, <i>et al.</i>	(1382)
ABR Decarbonization-Nitrosation Coupled with ANAMMOX to Treat Municipal Wastewater	LI Tian, CAO Jia-wei, XIE Feng-lian, <i>et al.</i>	(1390)
Start-up Performance and Sludge Characteristics of Single-stage Autotrophic Nitrogen Removal System with Granular Sludge at Low Ammonia Nitrogen Concentration at Room Temperature	XIE Lu-lin, WANG Jian-fang, QIAN Fei-yue, <i>et al.</i>	(1396)
ANAMMOX Reactor with Two Kinds of Inoculated Sludge: Start-up and Kinetics Characteristics	REN Jun-yi, CHEN Lin-yi, LI Hui-chun, <i>et al.</i>	(1405)
Operation Characteristics of the Biofilm CANON Reactor During the Temperature Reduction Process	FU Kun-ming, LIAO Min-hui, ZHOU Hou-tian, <i>et al.</i>	(1412)
Nitrogen Removal Characteristics and Analysis of Microbial Community Structure in an IEM-UF Simultaneous Separation and Denitrification System	LIU Zi-qi, ZHANG Yan, MA Xiang-shan, <i>et al.</i>	(1419)
Effect of Temperature on the Activity Kinetics of <i>Nitrobacter</i>	YU Xue, SUN Hong-wei, LI Wei-wei, <i>et al.</i>	(1426)
Enhancement for Anaerobic Digestion of Waste Activated Sludge Based on Microwave Pretreatment Combined with Zero Valent Iron	NIU Yu-tong, LIU Ji-bao, MA Shuang, <i>et al.</i>	(1431)
Effects of Environmental Factors on Tetracyclines and Macrolides Resistance Genes in Cattle Manure Composting Systems	PENG Jing, WANG Ke, GU Yue, <i>et al.</i>	(1439)
Effect of Environmental Factors on Variation Characteristics of Soil Microbial Respiration and Its Temperature Sensitivity	ZHANG Yan-jun, GUO Sheng-li	(1446)
Response of Soil Respiration and Its Components to Simulated Acid Rain in a Typical Forest Stand in the Three Gorges Reservoir Area	LI Yi-fan, WANG Yu-jie, WANG Bin, <i>et al.</i>	(1457)
Effects of Fertilization on the Nitrogen Residual Amounts and Leaching from Citrus Orchard Soil in the Three Gorges Reservoir Area	WANG Tian, HUANG Zhi-lin, ZENG Li-xiong, <i>et al.</i>	(1468)
Microbial Carbon Source Metabolic Profile in Rice Rhizosphere and Non-rhizosphere Soils with Different Long-term Fertilization Management	NING Zhao, CHENG Ai-wu, TANG Hai-ming, <i>et al.</i>	(1475)
Characterization of Soil Organic Carbon Mineralization Under Different Gradient Carbon Loading in Paddy Soil	TONG Yao-yao, WANG Ji-fei, ZHU Zhen-ke, <i>et al.</i>	(1483)
Soil Organic Carbon Distribution and Components in Different Plant Communities Along a Water Table Gradient in the Huixian Karst Wetland in Guilin	XU Guang-ping, LI Yan-qiong, SHEN Yu-yi, <i>et al.</i>	(1491)
Distribution of Organic Carbon in Soil Aggregates from Four Kinds of Forest Vegetation on Jinyun Mountain	WANG Fu-hua, LÜ Sheng, HUANG Rong, <i>et al.</i>	(1504)
Review of Research on the Impacts of Atmospheric Pollution on the Health of Residents	QIN Yao-chen, XIE Zhi-xiang, LI Yang	(1512)