

# 环境科学

(HUANJING KEXUE)

ENVIRONMENTAL SCIENCE

第38卷 第6期

Vol.38 No.6

2017

中国科学院生态环境研究中心 主办  
科学出版社 出版



目次

PM<sub>2.5</sub>浓度空间分异模拟模型对比:以京津冀地区为例 ..... 吴健生,王茜,李嘉诚,涂媛杰(2191)

北京地区近35年大气污染扩散条件变化 ..... 郭淳薇,孙兆彬,李梓铭,张小玲,杨慧玲(2202)

北京市典型区域夏季降水及其对大气污染物的影响 ..... 韩力慧,张海亮,向欣,张鹏,程水源,魏巍(2211)

北京山谷风环流特征分析及其对PM<sub>2.5</sub>浓度的影响 ..... 董群,赵普生,王迎春,苗世光,高健(2218)

北京市建筑施工扬尘排放特征 ..... 薛亦峰,周震,黄玉虎,王堃,聂滕,聂磊,秦建平(2231)

生物质成型燃料锅炉挥发性有机物排放特征 ..... 吴昌达,张春林,白莉,沈丽冉,王伯光,刘军,杨立辉(2238)

广州番禺大气成分站复合污染过程VOCs对O<sub>3</sub>与SOA的生成潜势 ..... 邹宇,邓雪娇,李菲,殷长泰(2246)

南京北郊大气臭氧周末效应特征分析 ..... 王俊秀,安俊琳,邵平,邹嘉南,林旭,张玉欣(2256)

亚热带稻区大气氨/铵态氮污染特征及干湿沉降 ..... 王杰飞,朱潇,沈健林,曾冠军,王娟,吴金水,李勇(2264)

宣威肺癌高发区燃煤排放颗粒物中铁的价态及其氧化性 ..... 王强翔,谭正莹,赵慧,李继华,田林玮,王青耀,米持真一,吕森林(2273)

垃圾焚烧厂二噁英污染及厂区工人呼吸暴露评估 ..... 杜国勇,汪倩,张姝琳,张素坤,邓春萍,张洪铭,朱盟翔,蒋昕,朱成旺,任燕玲(2280)

重庆市新型干法水泥厂汞排放特征 ..... 张成,张雅惠,王永敏,王定勇,罗程钟,徐凤,何秀清(2287)

轻型汽油车简易瞬态工况法与定容全流稀释采样法(CVS)的排放相关性 ..... 王鸿宇,黄成,胡馨遥,李莉,陈勇航,徐健(2294)

不同排放标准公交车燃用生物柴油颗粒物排放特性 ..... 楼狄明,赵成志,徐宁,谭丕强,胡志远(2301)

西江水氧同位素组成的空间变化及环境意义 ..... 许琦,李建鸿,孙平安,何师意,于爽(2308)

基于SWAT与DNDC模型对比研究亚热带流域氮淋溶与输出过程 ..... 韩宁,陈维梁,高扬,郝卓,于贵瑞(2317)

三峡库区澎溪河与磨刀溪电导率等水质特征与水华的关系比较 ..... 姜伟,周川,纪道斌,刘德富,任豫霜,Douglas Haffner,谢德体,张磊(2326)

滇池草海间隙水与上覆水氮磷时空变化特征 ..... 王一茹,王圣瑞,焦立新,张云,高秋生,杨枫(2336)

香溪河沉积物、间隙水的磷分布特征及释放通量估算 ..... 罗玉红,聂小倩,李晓玲,戴泽龙,胥焱,黄应平(2345)

大冶湖表层水和沉积物中重金属污染特征与风险评价 ..... 张家泉,田倩,许大毛,占长林,刘婷,姚瑞珍,刘先利,肖文胜(2355)

海水淡化低温多效蒸馏工艺(LT-MED)沿程溴代消毒副产物的生成 ..... 齐菲,孙迎雪,杨哲,胡春芳,常学明,胡洪营(2364)

两种水体铜配合容量测试方法的适用性比较及应用 ..... 王晨焱,姜括,谢文龙,汪磊(2373)

高地下水地区透水铺装控制径流污染的现场实验 ..... 金建荣,李田,时珍宝(2379)

稳定型纳米零价铁去除地下水中2,4-二氯苯酚 ..... 张永祥,常杉,李飞,徐毅,高维春(2385)

超声、紫外增强H<sub>2</sub>O<sub>2</sub>/KI降解磺胺甲基嘧啶 ..... 魏红,孙博成,杨小雨,李克斌(2393)

不同铅负载量改性膨润土对水中磷酸盐吸附作用的对比 ..... 姜博汇,林建伟,詹艳慧,邢云青,黄宏,储鸣,王星星(2400)

铁炭内电解垂直流人工湿地对污水厂尾水深度脱氮效果 ..... 郑晓英,朱星,周翔,徐亚东,王菊,韦诚,高雅洁,周徽(2412)

组合生物滤池对养殖废水的净化效率及影响因素分析 ..... 张世羊,张胜花,张翔凌,王广军(2419)

温度对聚磷菌活性及基质竞争的影响 ..... 张玲,彭党聪,常蝶(2429)

海洋厌氧氨氧化菌的富集培养及其脱氮特性 ..... 冯莉,于德爽,李津,单晓静,杨振琳(2435)

不同生物过滤系统铵态氮转化速率及生物膜特性分析 ..... 周洪玉,韩梅琳,仇天雷,高敏,孙兴滨,王旭明(2444)

磷酸盐对厌氧氨氧化活性污泥脱氮效能的影响 ..... 周正,刘凯,王凡,林兴,李祥,黄勇,顾澄伟(2453)

碳源胁迫下脱氮除磷颗粒污泥性能变化及其机制 ..... 秦诗友,陈威,马兆瑞,刘小英,陈晓国,余文韬,夏媛媛,黄健(2461)

外源Ca<sup>2+</sup>对SBR启动期活性污泥胞外多聚物的动态影响 ..... 任丽飞,杨新萍,张雯雯(2470)

膨胀污泥中丝状菌的分离鉴定与特性分析 ..... 张崇森,牛全睿,徐雨梅,王院梅,王岱,武少华(2477)

反硝化悬浮填料适用性及其微生物群落结构解析 ..... 谭阳,李激,徐巧,付磊,尤世界,王硕(2486)

硫代硫酸钠对排硫硫杆菌固碳能力的影响及其作用机制 ..... 李欢,王磊,王亚楠(2496)

关帝山森林土壤真菌群落结构与遗传多样性特征 ..... 乔沙沙,周永娜,柴宝峰,贾彤,李鑫(2502)

基于受体模型与地统计的城市居民区土壤重金属污染源解析 ..... 陈秀端,卢新卫(2513)

基于蒙特卡罗模拟的土壤环境健康风险评价:以PAHs为例 ..... 佟瑞鹏,杨校毅(2522)

Eh、pH和铁对水稻土砷释放的影响机制 ..... 钟松雄,尹光彩,陈志良,林亲铁,黄润林,刘德玲,彭焕龙,黄玲,王欣,蒋晓璐(2530)

典型土壤不同提取态Cd与水稻吸收累积的关系 ..... 陈齐,邓潇,陈珊,侯红波,彭佩钦,廖柏寒(2538)

复合改良剂对Cd污染稻田早晚稻产地修复效果 ..... 陈立伟,杨文骏,辜娇峰,周航,高子翔,廖柏寒(2546)

两种钝化剂对土壤Pb、Cd、As复合污染的菜地修复效果 ..... 田桃,雷鸣,周航,杨文骏,廖柏寒,胡立琼,曾敏(2553)

大豆和小麦根系对非的吸持作用及其生物有效性 ..... 王红菊,李倩倩,沈羽,顾若尘,盛好,占新华(2561)

源自腐殖土的溶解性有机质组分对棕壤和黑土吸附苯并三唑的影响 ..... 杨宁伟,毕二平(2568)

地形、树种和土壤属性对喀斯特山区土壤胞外酶活性的影响 ..... 罗攀,陈浩,肖孔操,杨利琼,文丽,李德军(2577)

长期定位有机物料还田对关中平原冬小麦-玉米轮作土壤N<sub>2</sub>O排放的影响 ..... 郝耀旭,刘继璇,袁梦轩,周应田,杨学云,顾江新(2586)

基于大气被动式采样的人体头发中类二噁英多氯联苯暴露的途径 ..... 袁浩东,白瑶,李秋旭,王英,金军(2594)

广西刁江野生鱼类重金属积累特征及其健康风险评价 ..... 王俊能,马鹏程,张丽娟,陈棉彪,黄楚珊,柳晓琳,胡国成,许振成(2600)

活性炭在中高温条件下对玉米秸秆厌氧发酵的影响 ..... 甘荣,葛明民,刘勇迪,贾红华,闫志英,雍晓雨,吴夏莞,周俊(2607)

工艺过程源和溶剂使用源挥发性有机物排放成分谱研究进展 ..... 王红丽,杨肇勋,景盛翱(2617)

《环境科学》征稿简则(2452) 《环境科学》征订启事(2560) 信息(2201, 2230, 2384)

# 碳源胁迫下脱氮除磷颗粒污泥性能变化及其机制

秦诗友<sup>1,2</sup>, 陈威<sup>1</sup>, 马兆瑞<sup>2,3</sup>, 刘小英<sup>2,4\*</sup>, 陈晓国<sup>2</sup>, 余文韬<sup>2</sup>, 夏媛媛<sup>2</sup>, 黄健<sup>2</sup>

(1. 武汉科技大学城市建设学院, 武汉 430065; 2. 武汉理工大学土木工程与建筑学院, 武汉 430070; 3. 威海市建筑设计院有限公司, 威海 264200; 4. 武汉理工大学资源与环境工程学院, 武汉 430070)

**摘要:** 在 SBR 反应器中, 逐步提高颗粒污泥反应器进水葡萄糖比例(醋酸钠/葡萄糖比分别为 1:0、3:1、1:1、1:3 和 0:1, 以 COD 计)研究碳源胁迫下, 5 个阶段污泥的物理性能、生化反应性能、胞外聚合物(extracellular polymeric substances, EPS)、磷组分以及反应器脱氮除磷等变化。反应器运行 705 d 结果表明, 阶段 IV 污泥结构松散, 平均粒径仅为 0.5 mm, 污泥释/吸磷速率、反硝化速率及总磷(total phosphorus, TP)含量最低, 系统脱氮除磷效果最差; 阶段 I 和 II, 污泥释/吸磷速率和反硝化速率较快, TP 在  $72.36 \text{ mg}\cdot\text{g}^{-1}$  以上, EPS 高达  $350 \text{ mg}\cdot\text{g}^{-1}$  左右, 系统氮和磷去除率在 94% 以上; 阶段 V 中, 生化速率略慢于阶段 I 和 II, 污泥 TP  $69.60 \text{ mg}\cdot\text{g}^{-1}$ , 糖原高达  $224.18 \text{ mg}\cdot\text{g}^{-1}$ , EPS 约为  $200 \text{ mg}\cdot\text{g}^{-1}$ , 系统表现出良好的脱氮除磷性能。各阶段污泥中, 与 Ca 结合态磷(Ca-P)是污泥中磷的主要构成, 无机磷(inorganic phosphorus, IP)对颗粒污泥除磷有重要影响。

**关键词:** 碳源; 颗粒污泥; 脱氮除磷; 磷的组分; EPS

中图分类号: X703.1 文献标识码: A 文章编号: 0250-3301(2017)06-2461-09 DOI: 10.13227/j.hjxx.201610027

## Characteristics and Mechanism of Biological Nitrogen and Phosphorus Removal Granular Sludge Under Carbon Source Stress

QIN Shi-you<sup>1,2</sup>, CHEN Wei<sup>1</sup>, MA Zhao-rui<sup>2,3</sup>, LIU Xiao-ying<sup>2,4\*</sup>, CHEN Xiao-guo<sup>2</sup>, YU Wen-tao<sup>2</sup>, XIA Yuan-yuan<sup>2</sup>, HUANG Jian<sup>2</sup>

(1. School of Urban Construction, Wuhan University of Science and Technology, Wuhan 430065, China; 2. School of Civil Engineering & Architecture, Wuhan University of Technology, Wuhan 430070, China; 3. Weihai Architectural Design Institute Co., Ltd., Weihai 264200, China; 4. School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan 430070, China)

**Abstract:** In SBR reactor, the mature granular sludge fed with sodium acetate was gradually cultivated with different carbon sources (sodium acetate/glucose ratio was 1:0, 3:1, 1:1, 1:3 and 0:1, in terms of COD, respectively). During the five stages, the physical, biochemical properties, extracellular polymeric substances (EPS), phosphorus fractions and nitrogen and phosphorus removal efficiency of granular sludge were studied. 705 days' experimental results were showed as follows. At stage IV, the granular sludge had the smallest diameter of 0.5 mm; moreover the phosphorus release/uptake rate, denitrification rate and the total phosphorus (TP) content were the lowest. While at stages I and II, the phosphorus release/uptake and denitrification rates were the highest, meanwhile, the TP content reached up to  $72.36 \text{ mg}\cdot\text{g}^{-1}$ , and the EPS content was about  $350 \text{ mg}\cdot\text{g}^{-1}$ , as a result, the nitrogen and phosphorus removal efficiencies were both over 94%. Nevertheless at stage V, the biochemical rates were slightly slower than values of stages I and II, simultaneously the TP, glycogen and EPS contents in sludge were maintained at  $69.60 \text{ mg}\cdot\text{g}^{-1}$ ,  $224.18 \text{ mg}\cdot\text{g}^{-1}$  and  $200 \text{ mg}\cdot\text{g}^{-1}$ , respectively, while high nitrogen and phosphorus removal efficiency was obtained. During all stages, Ca-P was the main phosphorus fraction, and inorganic phosphorus(IP) was closely related to phosphorus removal of granular sludge.

**Key words:** carbon source; granular sludge; nitrogen and phosphorus removal; phosphorus fractionation; extracellular polymeric substances (EPS)

好氧颗粒污泥由微生物自凝聚形成,与絮状污泥相比,具有沉速快、生物相丰富、抗冲击负荷能力强等优点,被认为是最有前景的污水处理技术之一<sup>[1]</sup>。目前,好氧颗粒污泥已广泛运用于处理城市污水、重金属污水、印染废水及高浓度食品废水等<sup>[2-5]</sup>。其中,利用颗粒污泥进行脱氮除磷对研究颗粒污泥形成与稳定及同步去除氮磷机制具有重要意义。

大量研究表明<sup>[6-8]</sup>,碳源对污泥物理性能、菌

落结构、脱氮除磷等具有显著影响。王迪等<sup>[6]</sup>发现,醋酸钠和葡萄糖为碳源培养的颗粒污泥,两者粒径和污泥容积指数(sludge volume index, SVI)相近(粒径分别为 1.1 mm 和 1.0 mm, SVI 分别为  $31 \text{ mL}\cdot\text{g}^{-1}$  和  $26 \text{ mL}\cdot\text{g}^{-1}$ ),但前者不含丝状菌而后者则

收稿日期: 2016-10-08; 修订日期: 2016-12-25

基金项目: 国家自然科学基金项目(21407114); 2016 年度国家大学生创新创业训练计划项目(20161049706006)

作者简介: 秦诗友(1991~),男,硕士研究生,主要研究方向为污水脱氮除磷, E-mail: gutenday@126.com

\* 通信作者, E-mail: xy2000225@126.com

有少量丝状菌存在;高景峰等<sup>[9]</sup>进一步证明,以挥发性脂肪酸(volatile fatty acids, VFAs)为碳源时,短杆菌较多,球菌较少,而以葡萄糖为碳源时球菌多,且存在大量与聚糖菌(glycogen accumulating organisms, GAOs)有关的八叠球菌. 但总体而言,这方面研究较少.

碳源对生物除磷有重要影响. 普遍认为,以醋酸、丙酸等 VFAs 为碳源时,聚磷菌(polyphosphate accumulating organisms, PAOs)易于富集,而以葡萄糖为碳源时,GAOs 会大量富集导致系统非稳态运行,抑制 PAOs 生长而导致反应器丧失除磷能力<sup>[10~16]</sup>. 但也有研究者发现,葡萄糖为碳源时 PAOs 数量远高于 GAOs 数量(两者分别为 45.5% 和 4.26%)<sup>[17]</sup>. 相比较而言,碳源对脱氮影响较小. 醋酸钠反应器脱氮效率在 90% 以上,尽管反硝化速率是葡萄糖为碳源的 1.37 倍<sup>[11, 18~20]</sup>,但葡萄糖反应器脱氮效率也在 80% 以上. 综上所述,碳源对除磷的影响有待更进一步研究.

另外,研究者发现,碳源对污泥胞外聚合物(extracellular polymeric substances, EPS)、糖原及磷的形态也有影响. Ye 等发现<sup>[21]</sup>,分别以醋酸钠和葡萄糖为碳源时, EPS 中蛋白质(protein, PN)均为主要组成部分且质量分数相当,但后者多糖(polysaccharide, PS)质量分数较高(PN、PS 与污泥稳定性有重要联系<sup>[1]</sup>),而其他学者以葡萄糖为碳源时发现<sup>[22, 23]</sup>, EPS 中 PS 质量分数显著高于 PN. 污泥中总磷(total phosphorus, TP)和总糖是系统中 PAOs 和 GAOs 数量重要指示<sup>[24]</sup>,醋酸钠为碳源时,污泥中总糖较低,而 TP 较高,除磷能力强<sup>[16]</sup>. 近年来,研究者进一步发现污泥中磷的形态与磷去除机制有关,葡萄糖与醋酸钠(配比为 1:1)混合碳源时,无机磷(inorganic phosphorus, IP)中铁与铝结合态磷(Fe/Al-P)为污泥中磷的主要存在形式,然而一些研究者认为除磷系统中与 Ca 结合的 Ca-P 为主要形式,这可能与其进水组分有关<sup>[25, 26]</sup>. 总之, EPS、TP 和总糖及磷组份的差异是否与碳源基质有关,还有待于深入研究.

因此,本试验在 SBR 反应器中,以成熟脱氮除磷颗粒污泥(醋酸钠为碳源)为研究对象,逐级增加葡萄糖比例,最终培养成葡萄糖为唯一碳源的好氧颗粒污泥,研究此碳源胁迫过程中颗粒污泥物理、生化性能的变化,深入探究其相互关系,进一步丰富碳源对颗粒污泥脱氮除磷的影响研究.

## 1 材料与方法

### 1.1 试验装置及运行方式

试验用 SBR 反应器(图 1)由圆柱形双层有机玻璃制成,总容积 5 L,有效容积 4 L,内层为反应主体部分,直径 16 cm,高 25 cm,外层为循环水用于温度控制. 反应器体积交换率为 50%, pH 值为 7.5 ~ 8.5,温度为 26℃ 左右,搅拌转速为 96 r·min<sup>-1</sup> 左右,好氧段曝气流量约为 0.45 ~ 0.80 L·min<sup>-1</sup>. 反应器每周运行 288 min,其中包括进水 1 min、厌氧 80 min、曝气 193 min、沉淀 5 min、排水 5 min 及闲置 4 min,好氧末端排出一定量泥水混合物,控制污泥龄为 23 d 左右.

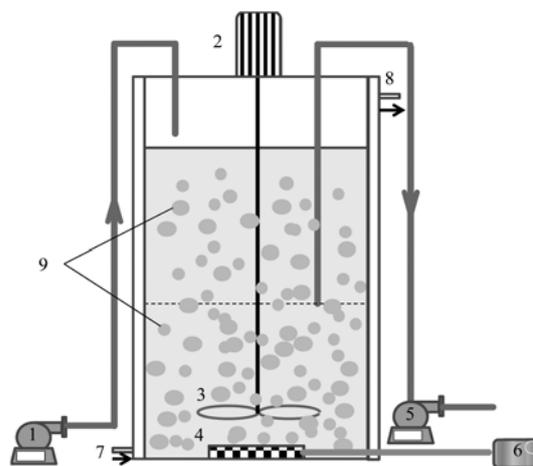


图 1 SBR 反应器装置示意  
1. 进水泵;2. 搅拌电机;3. 搅拌桨;4. 微孔曝气盘;5. 出水泵;  
6. 空气泵;7. 循环水进水口;8. 循环水出水口;9. 颗粒污泥

图 1 SBR 反应器装置示意

Fig. 1 Schematic diagram of the sequencing batch reactor

### 1.2 试验用水

试验用水由人工配制,其组成成分见表 1.

### 1.3 试验方法

本次试验按进水 COD 组成成分不同分为 5 阶

表 1 进水成分

进水成分	$\rho/\text{mg}\cdot\text{L}^{-1}$	微量元素组分	$\rho/\text{mg}\cdot\text{L}^{-1}$
COD	400 ~ 440(以 O 计)	MgSO <sub>4</sub> ·H <sub>2</sub> O	50
CaCl <sub>2</sub>	60 ~ 70(以 Ca 计)	FeCl <sub>3</sub> ·6H <sub>2</sub> O	4.5
NH <sub>4</sub> <sup>+</sup> -N	40	EDTA	30
PO <sub>4</sub> <sup>3-</sup> -P	15	H <sub>3</sub> BO <sub>3</sub>	0.45
蛋白胨	26	CuSO <sub>4</sub> ·5H <sub>2</sub> O	0.09
微量元素	5 mL·(13 L) <sup>-1</sup>	KI	0.54
		MnCl <sub>2</sub> ·2H <sub>2</sub> O	0.36
		CoCl <sub>2</sub> ·6H <sub>2</sub> O	0.45
		ZnSO <sub>4</sub> ·7H <sub>2</sub> O	0.36
		Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	0.18

段,其中阶段 I 以醋酸钠为唯一碳源,阶段 II 至阶段 IV 碳源为醋酸钠和葡萄糖,其对 COD 的贡献比例分别为 3:1、1:1 和 1:3,阶段 V 以葡萄糖为唯一碳源,反应器共运行 705 d. 通过试验研究碳源胁迫下,各阶段污泥形态,氮和磷的去除状况及其最大反应速率,污泥中 EPS、总糖及 TP 含量及污泥中磷形态,探讨碳源对微生物形态、反应速率及污泥形态的影

响,分析碳源种类与微生物形态、EPS、磷的形态之间的关系.

#### 1.4 分析测试方法

##### 1.4.1 SMT 法测定污泥中磷的形态及含量

SMT 法将污泥中 TP 形态分为 4 类,分别为 Fe/Al-P、Ca-P、有机磷(organic phosphorus, OP)和 IP,其分析方法如图 2 所示.

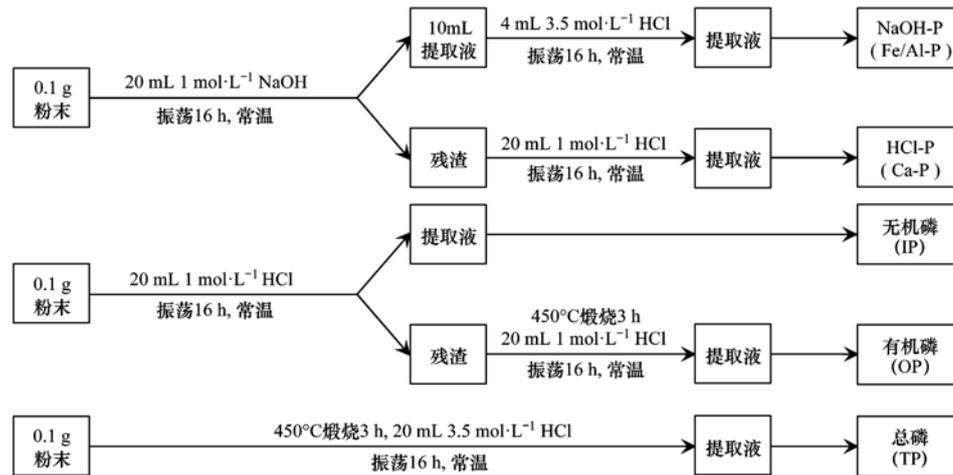


图 2 SMT 分析方法<sup>[26]</sup>

Fig. 2 SMT protocol

##### 1.4.2 污泥中 EPS 提取及测试

本试验采用加热法提取污泥中 EPS,其具体方法如下:取适量泥水混合物,用去离子水离心清洗(6 000 r·min<sup>-1</sup>, 10 min)3 次,撇去上清液,向污泥中加 EPS 提取液(2 mmol·L<sup>-1</sup> Na<sub>3</sub>PO<sub>4</sub>, 4 mmol·L<sup>-1</sup> NaH<sub>2</sub>PO<sub>4</sub>, 9 mmol·L<sup>-1</sup> NaCl 和 1 mmol·L<sup>-1</sup> KCl, pH = 7)恢复至原体积,置于沸水浴 15 min(每 5 min 取出进行振荡),结束后样品经离心(12 000 r·min<sup>-1</sup>, 15 min)后,取上清液测定污泥中 EPS;EPS 中 PS、PN 和腐殖酸(humic acid, HA)分别采用蒽酮法<sup>[27]</sup>和修正的福林酚法<sup>[28]</sup>测定,核酸(nucleic acid, NA)采用分光光度计(260 nm)测定.

##### 1.4.3 污泥反应速率测定

通过烧杯试验测定污泥去除氮和磷的生化反应速率,其具体操作如下:从反应器中取一定量颗粒污泥混合液,经离心清洗后置于烧杯试验装置中定容,然后分别投加特定试验基质(释磷试验投加相应碳源,吸磷试验在厌氧释磷结束后清洗后再投加磷并进行曝气,硝化试验投加氮和碳酸氢钠并进行曝气,反硝化试验投加碳源和氮,基质必须充足),控制反应过程中温度(25 ~ 28℃)和 pH 值(7.0 ~ 7.5),在不同时刻测定相应的氮和磷的质量浓度,分别绘制

$\rho$ - $t$  曲线,利用曲线的最大斜率计算得到污泥最大释磷、吸磷、硝化及反硝化速率.

##### 1.4.4 常规指标

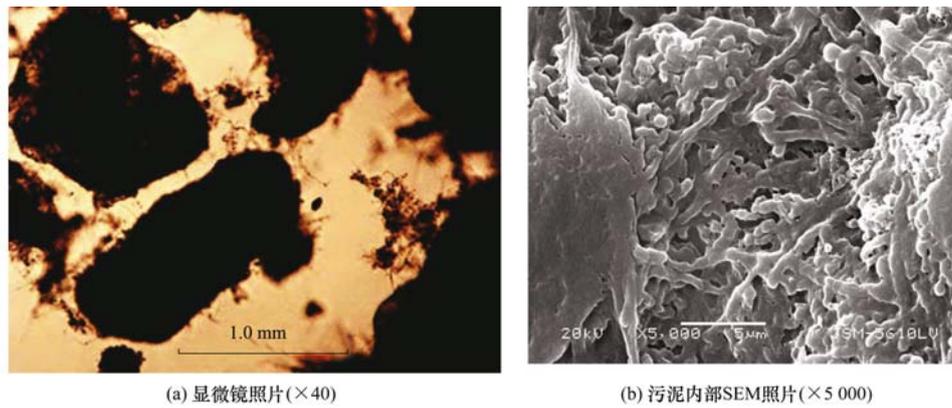
NH<sub>4</sub><sup>+</sup>-N、NO<sub>2</sub><sup>-</sup>-N、NO<sub>3</sub><sup>-</sup>-N、PO<sub>4</sub><sup>3-</sup>-P、MLSS、MLVSS 及 SVI 等参照文献[29]测定;颗粒污泥形态采用生物显微镜(舜宇 EX20, 宁波)和扫描电镜(JSM-IT300, 日本)进行观察;颗粒污泥经超声(新芝 JY92-II, 宁波)预处理后,采用蒽酮比色法测污泥中总糖.

## 2 结果与讨论

### 2.1 醋酸钠为碳源(阶段 I)颗粒污泥的性能

阶段 I 颗粒污泥反应器运行 123 d,该颗粒污泥[图 3(a)]呈淡黄色,边界清晰,呈球形或椭球形,平均粒径在 1.0 mm 左右,SVI 在 38.97 mL·g<sup>-1</sup> 以下;颗粒污泥表面和内部生长着一定数量的丝状菌(图 3),球菌和短杆菌等微生物附着于丝状菌周围,污泥内存在一定数量的孔隙和空腔来传输微生物生长需要的营养物质和溶解氧[图 3(b)].

颗粒污泥系统在该阶段对氮和磷的去除状况见图 4(a). 123 d 内厌氧末端磷(P<sub>ant</sub>)由 60 mg·L<sup>-1</sup> 缓慢上升到近 120 mg·L<sup>-1</sup>,而出水磷维持在 0.78



(a) 显微镜照片( $\times 40$ ) (b) 污泥内部SEM照片( $\times 5\ 000$ )

图 3 阶段 I 颗粒污泥形态

Fig. 3 Morphology of the granular sludge in stage I

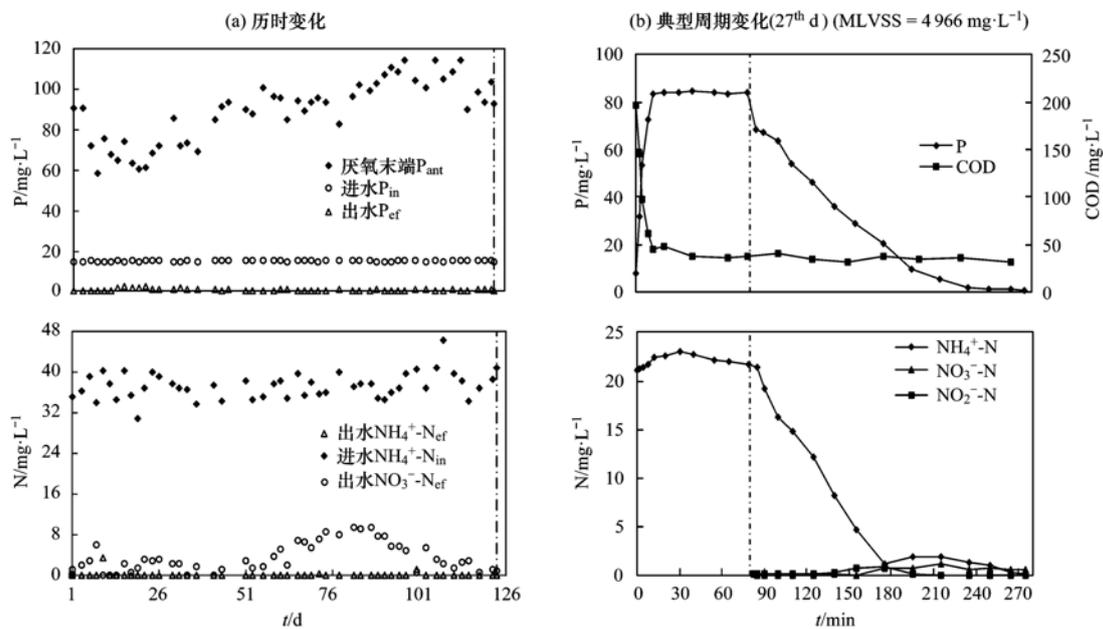


图 4 阶段 I 污泥脱氮除磷性能

Fig. 4 Performance of nitrogen and phosphorus removal at stage I

$\text{mg}\cdot\text{L}^{-1}$ 左右;出水 $\text{NH}_4^+\text{-N}$ 维持在 $0.14\ \text{mg}\cdot\text{L}^{-1}$ 以下,未检测出 $\text{NO}_2^-\text{-N}$ ,出水 $\text{NO}_3^-\text{-N}$ 开始56 d内较稳定(约为 $1.88\ \text{mg}\cdot\text{L}^{-1}$ ),之后逐渐上升,82 d达最大 $9.42\ \text{mg}\cdot\text{L}^{-1}$ ,然后逐渐降低至 $1.0\ \text{mg}\cdot\text{L}^{-1}$ 左右。

27 d时,反应器某一周期内颗粒污泥对营养物质的降解特性见图4(b)。厌氧段期间,8 min内COD由 $196.68\ \text{mg}\cdot\text{L}^{-1}$ 迅速下降到 $61.04\ \text{mg}\cdot\text{L}^{-1}$ ,最后维持至 $40\ \text{mg}\cdot\text{L}^{-1}$ 左右,最大降解速率为 $194.07\ \text{mg}\cdot(\text{g}\cdot\text{h})^{-1}$ 。磷在20 min内迅速上升到 $84.03\ \text{mg}\cdot\text{L}^{-1}$ ,最大释磷速率为 $64.68\ \text{mg}\cdot(\text{g}\cdot\text{h})^{-1}$ ,释磷总量为 $74.39\ \text{mg}\cdot\text{L}^{-1}$ ;好氧开始95 min内磷快速降低到 $9.38\ \text{mg}\cdot\text{L}^{-1}$ ,最大吸磷速率为 $33.34\ \text{mg}\cdot(\text{g}\cdot\text{h})^{-1}$ ,吸磷总量 $83.09\ \text{mg}\cdot\text{L}^{-1}$ 。厌氧段 $\text{NH}_4^+\text{-N}$ 略有下降,好氧段 $\text{NH}_4^+\text{-N}$ 由 $21.74$

$\text{mg}\cdot\text{L}^{-1}$ 下降到 $1.85\ \text{mg}\cdot\text{L}^{-1}$ ,期间最大硝化速率 $7.27\ \text{mg}\cdot(\text{g}\cdot\text{h})^{-1}$ ,好氧段结束时,磷、 $\text{NH}_4^+\text{-N}$ 、 $\text{NO}_x^-\text{-N}$ 均在 $1.0\ \text{mg}\cdot\text{L}^{-1}$ 以下。

## 2.2 碳源胁迫下颗粒污泥的性能变化

### 2.2.1 污泥表观形态

碳源胁迫下颗粒污泥形态及内部菌落的变化见表2及图5。从其中数据看出,阶段IV为污泥形态变化拐点,该阶段污泥粒径、边界及质地均有显著变化。内部菌落变化较小,球菌作为构成主体,丝状菌存在于各阶段,阶段V中观察到有少量杆菌,各阶段颗粒污泥都具有较好的沉降性能。

### 2.2.2 反应器脱氮除磷效果

由图6(a)可知,阶段II到阶段IV, $P_{\text{ant}}$ 由 $110\ \text{mg}\cdot\text{L}^{-1}$ 逐渐下降到 $15\ \text{mg}\cdot\text{L}^{-1}$ 以下,出水磷在352 d

表2 好氧颗粒污泥物理性状

Table 2 Physical and biological characteristics of aerobic granular sludge

阶段	颜色	形状	平均粒径 /mm	SVI /mL·g <sup>-1</sup>	表面边界	结构密实度	微生物形态
II (180 d)	浅黄	椭圆	1.5 (±0.2)	43.34	较光滑	密实	球菌、丝状菌
III (153 d)	黄	椭圆	1.8 (±0.3)	58.15	较光滑	密实	球菌、丝状菌
IV (124 d)	黄褐	不规则	0.5 (±0.2)	44.89	模糊	松散	球菌、丝状菌
V (125 d)	黄	椭圆	1.7 (±0.3)	31.3	光滑,较清晰	密实	球菌、丝状菌、杆菌

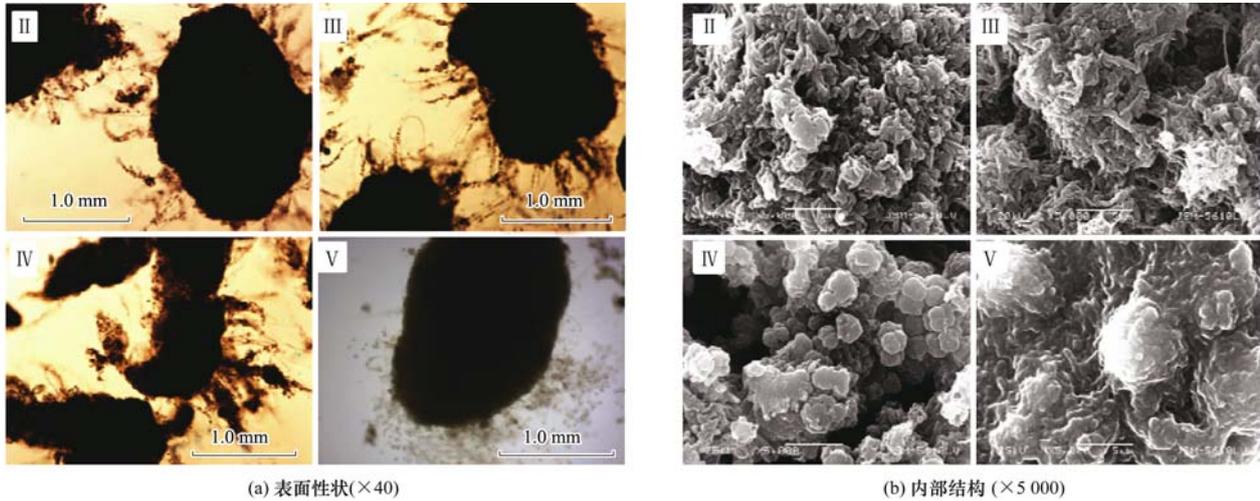


图5 碳源胁迫下颗粒污泥形态变化

Fig. 5 Morphology variations in different stages under carbon source stress

前约维持在  $1.04 \text{ mg}\cdot\text{L}^{-1}$ , 之后直到阶段IV末期呈上升趋势, 最高可达  $21.34 \text{ mg}\cdot\text{L}^{-1}$ , 阶段V中,  $P_{\text{ant}}$  由  $8.23 \text{ mg}\cdot\text{L}^{-1}$  缓慢上升到  $45.58 \text{ mg}\cdot\text{L}^{-1}$  并维持稳定, 出水磷则呈下降趋势, 到 644 d 降低为  $0.86 \text{ mg}\cdot\text{L}^{-1}$ . 较高的  $P_{\text{ant}}$  推断出, 系统中存在大量 PAOs, 有利于除磷.

图6(b)看出, 阶段II到阶段V, 出水  $\text{NH}_4^+\text{-N}$  和  $\text{NO}_2^-\text{-N}$  基本维持在  $1.0 \text{ mg}\cdot\text{L}^{-1}$  以下, 出水  $\text{NO}_3^-\text{-N}$  变化显著, 阶段II到阶段IV呈上升趋势, 阶段IV结束时, 其值高达  $21.75 \text{ mg}\cdot\text{L}^{-1}$ , 阶段V呈显著下降趋势, 由  $21.75 \text{ mg}\cdot\text{L}^{-1}$  下降到  $0.50 \text{ mg}\cdot\text{L}^{-1}$ . 从阶段II到阶段IV, 系统脱氮除磷性能逐级变差, 而进入阶段V后经过一定稳定时间, 系统同步脱氮除磷性能逐渐恢复.

上述结果看出, 颗粒污泥在碳源胁迫下, 虽保持良好的沉降性能, 但污泥形态和内部微生物构成发生了变化, 其中磷的变化更为显著. 例如, 阶段IV葡萄糖为主要进水碳源, 污泥形态发生了显著变化, 系统除磷能力丧失; 同时污泥粒径变小, 外部 DO 渗透破坏颗粒污泥内部微缺氧环境, 反硝化能力降低. 由此可见, 碳源是影响系统效果的重要因素.

### 2.3 不同阶段颗粒污泥其他性能参数转变

#### 2.3.1 颗粒污泥生化反应性能

取各阶段内不同时段污泥进行烧杯试验, 得到表3 污泥生化特性. 反应器由阶段I到阶段V运行过程中, 污泥最大释/吸磷速率、硝化速率和反硝化速率呈先降低后缓慢上升的趋势, MLSS 及 MLVSS 也有同样变化趋势.

表3 污泥生化反应性能

Table 3 Biochemical reaction characteristics of granular sludge

阶段	最大释磷速率 /mg·(g·h) <sup>-1</sup>	最大吸磷速率 /mg·(g·h) <sup>-1</sup>	最大硝化速率 /mg·(g·h) <sup>-1</sup>	最大反硝化速率 /mg·(g·h) <sup>-1</sup>	MLSS /mg·L <sup>-1</sup>	MLVSS /mg·L <sup>-1</sup>
I	57.88 ± 4.37	25.94 ± 5.23	9.70 ± 2.56	30.41 ± 4.32	8 057	5 475
II	50.51 ± 4.35	23.76 ± 3.69	9.85 ± 2.58	22.42 ± 5.68	6 584	4 557
III	34.83 ± 2.87	14.55 ± 2.64	8.25 ± 3.71	17.12 ± 3.26	3 799	2 515
IV	4.27 ± 0.68	1.27 ± 0.98	7.17 ± 1.78	8.25 ± 1.67	3 455	2 933
V	23.53 ± 2.69	9.88 ± 2.85	7.39 ± 1.87	18.78 ± 2.65	9 253	6 990

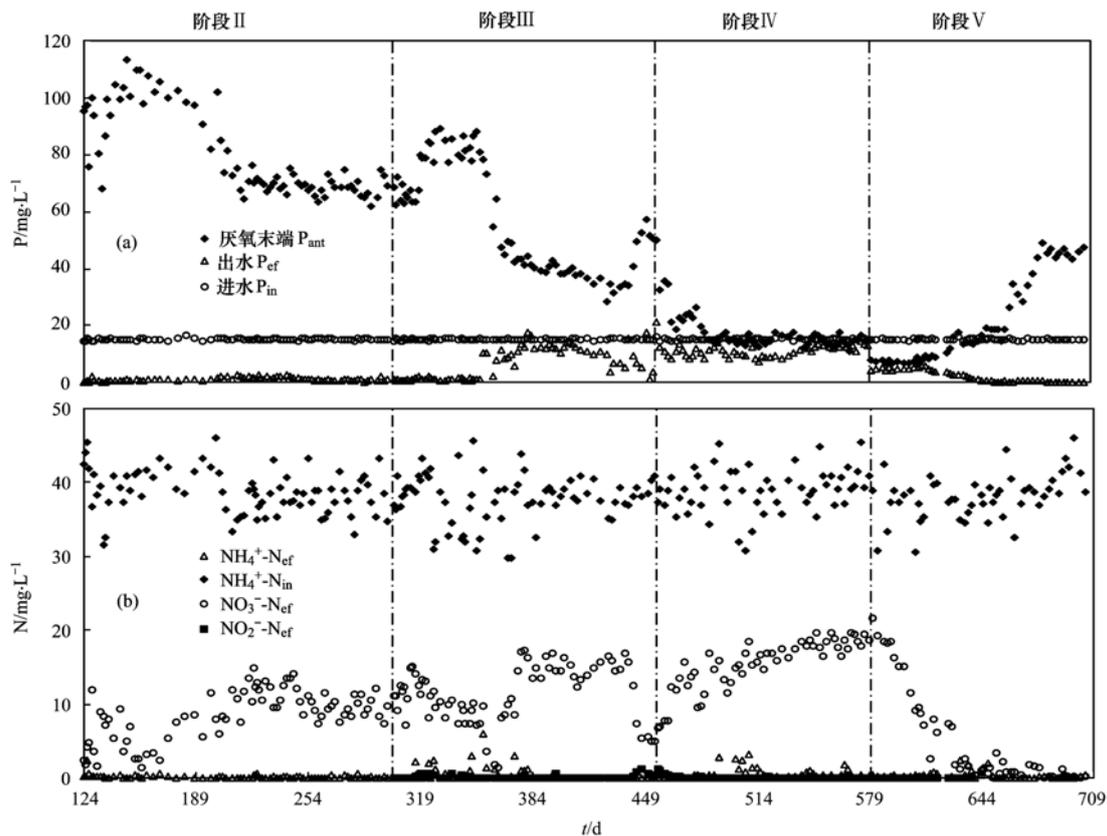


图 6 碳源胁迫下脱氮除磷历时变化

Fig. 6 Phosphorus and nitrogen changes in different stages under carbon source stress

结合图 4 和 6 看出,阶段 I 颗粒污泥最大释/吸磷速率快,系统除磷能力强,相比较而言,阶段 V 系统除磷能力也较强但其最大释/吸磷速率较慢;各阶段污泥龄在 23 d 左右,曝气量充足的情况下,系统硝化速率基本维持在  $7 \text{ mg} \cdot (\text{g} \cdot \text{h})^{-1}$  以上,出水基本没有  $\text{NH}_4^+ \text{-N}$ ,在较低出水  $\text{NO}_x^- \text{-N}$  下,阶段 I 相比阶段 V 具有更高的反硝化速率;阶段 IV,污泥浓度及生化反应速率最慢,此时颗粒污泥结构松散,微生物易于流失。

### 2.3.2 颗粒污泥中总磷和总糖

取各阶段好氧末端污泥测定其总糖与 TP 含量,其变化见表 4。随着进水中葡萄糖的增加,污泥中总糖由  $63.77 \text{ mg} \cdot \text{g}^{-1}$  显著上升到  $224.18 \text{ mg} \cdot \text{g}^{-1}$ ;而 TP 从阶段 I 到阶段 IV 则显著下降,最低为  $21.88 \text{ mg} \cdot \text{g}^{-1}$ ,阶段 V 又上升到  $69.60 \text{ mg} \cdot \text{g}^{-1}$ ,维持了较高水平。可见,葡萄糖为基质时有利于糖原的合成。

表 4 不同阶段颗粒污泥总糖与 TP 变化/ $\text{mg} \cdot \text{g}^{-1}$ Table 4 Total glycogen and total phosphorus of granular sludge in different stages/ $\text{mg} \cdot \text{g}^{-1}$ 

阶段	I	II	III	IV	V
总糖	63.77	161.22	204.17	209.17	224.18
TP	89.15	72.36	52.17	21.88	69.60

结合图 4、图 6 和表 4 可以看出,阶段 I、II 和 V 中,污泥中 TP 在  $69.60 \text{ mg} \cdot \text{g}^{-1}$  以上,此时污泥中总糖虽然差别很大,但系统平均除磷率均在 80% 以上,而阶段 IV 污泥总糖在  $200 \text{ mg} \cdot \text{g}^{-1}$  以上,低于阶段 V 总糖,其 TP 最低仅为  $21.88 \text{ mg} \cdot \text{g}^{-1}$ ,系统几乎丧失除磷能力。这可能由于系统中 PAOs 数量减少,而以球菌形式存在的 GAOs 数量增多引起,导致厌氧段合成胞内储存物质的种类和途径发生了变化,

影响磷的去除<sup>[30, 31]</sup>;同时生物除磷污泥总糖含量较高,间接说明 GAOs 与 PAOs 共存,这一结论与 Beer 的结果一致<sup>[32]</sup>。

最新研究发现,污泥中磷组分与污泥除磷有直接关系。为此课题组利用 SMT 法研究了不同阶段污泥中磷组分情况(见表 5),发现 IP 为主要组成,IP 中 Ca-P 质量分数在 60% 以上,这与本试验中进水投加  $\text{CaCl}_2$  有关;阶段 IV 中, Ca-P 和 Fe/Al-P 在

TP 中的质量分数最低分别为 40.60% 和 15.19%, 而对应此时污泥中 TP 和释/吸磷速率最低(见表 4 和表 3), 系统除磷能力最差; 而阶段 I 中其值最高分别为 57.34% 和 21.36%, 此时除磷能力最强. 其中, OP 与微生物代谢有关<sup>[25, 33, 34]</sup>, 而 Ca-P 和 Fe/Al-P 不仅作为构成颗粒污泥的重要晶核存在<sup>[35]</sup>, 同时参与了聚磷合成及营养物质的运输, 影响系统的除磷.

表 5 SMT 法测定污泥中磷的构成/%

Table 5 Different phosphorus fractions of granular sludge detected by SMT protocol/%

阶段	TP		IP	
	OP	IP	Fe/Al-P	Ca-P
I	6.3	93.7	22.8	61.2
II				
III	25.5	74.5	22.3	60.9
IV	34.2	65.8	23.1	61.7
V	26.4	73.6	21.2	67.5

### 2.3.3 颗粒污泥中 EPS

图 7 显示不同阶段颗粒污泥 EPS 组成情况, 阶段 I 和 II 污泥 EPS 在  $350 \text{ mg} \cdot \text{g}^{-1}$  左右, 而阶段 IV 和 V 污泥 EPS 维持在  $200 \text{ mg} \cdot \text{g}^{-1}$  左右; 各阶段污泥 EPS 中, PN 为其主要组成部分, PN 与 PS 是引起 EPS 变化主要因素. 疏水性 PN 有利于污泥稳定, 亲水性 PS 与污泥解体有关, PN/PS 反映颗粒污泥的稳定性<sup>[36~39]</sup>. 结合图 3 和图 5 可以看出, PN/PS 变化与污泥形态结构变化呈显著正相关, PN/PS 在 4 以上时, 颗粒污泥表现出良好的形态结构.

综上所述, EPS 作为运输细胞内外物质的通道, 间接反映了微生物生长状况. 以醋酸钠为主碳源的系统中, 具有较高释/吸磷速率, 系统除磷能力较强, EPS 分泌量较高, 当葡萄糖为单一碳源时, 虽然系统可以维持较高除磷率, 但污泥释/吸磷速率显著减慢, EPS 总量也随之降低; 另外, 阶段 I 和 V 中, 污泥中存在一定数量的杆菌(反硝化微生物主要以杆菌为主, 但其极易流失), 反硝化速率较快, 系统具有较高脱氮能力.

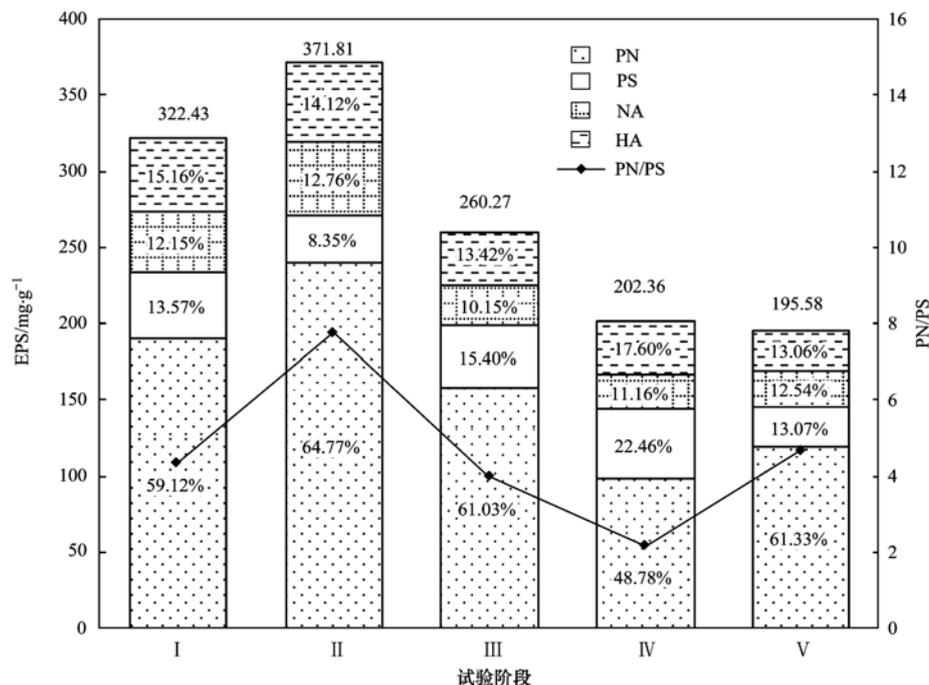


图 7 碳源胁迫下颗粒污泥 EPS 的变化

Fig. 7 Changes of EPS in granular sludge under carbon source stress

## 3 结论

(1) 好氧颗粒在碳源胁迫下, 污泥物理形态和菌种结构发生了较显著变化, 丝状菌和球菌广泛存在, 尤其以葡萄糖为主的碳源系统中, 球菌数量较多.

(2) 以醋酸钠为主碳源系统中, 污泥释/吸磷速率, 污泥 TP 均较高, 系统表现出良好的除磷效果; 当增加进水中葡萄糖比例时, 污泥释/吸磷速率降低至接近零, 污泥中 TP 降低到  $21.88 \text{ mg} \cdot \text{g}^{-1}$ , 系统丧失除磷能力; 当葡萄糖为唯一碳源时, 污泥释/吸磷速率和污泥 TP 均呈现回升, 系统获得较好的除磷

效果.

(3)不同运行阶段污泥生化反应速率表明,碳源不影响硝化反应,而以短杆菌形态存在的反硝化菌由于颗粒污泥结构的变化而流失,导致出水 $\text{NO}_3^-$ -N较高,最高达 $21.75 \text{ mg}\cdot\text{L}^{-1}$ .当污泥性能稳定,葡萄糖为唯一碳源时,污泥中仍含少量短杆菌,反硝化速率也提高到 $18.78 \text{ mg}\cdot(\text{g}\cdot\text{h})^{-1}$ ,保证系统具有较高的氮去除率.

(4)污泥中IP占TP的65%以上,其中Ca-P是构成IP的主要部分;另外,醋酸钠为主的碳源系统中,颗粒污泥EPS最高,随着进水葡萄糖的增加,EPS逐渐降低,当葡萄糖为单一碳源时,EPS最低;PN/PS在4以上时,颗粒污泥结构稳定.

致谢:感谢武汉理工大学给排水实验室和课题组成员给予的帮助.

#### 参考文献:

- [1] Deng S, Wang L X, Su H J. Role and influence of extracellular polymeric substances on the preparation of aerobic granular sludge [J]. *Journal of Environmental Management*, 2016, **173**: 49-54.
- [2] Pronk M, de Kreuk M K, de Bruin B, *et al.* Full scale performance of the aerobic granular sludge process for sewage treatment[J]. *Water Research*, 2015, **84**: 207-217.
- [3] Liu W, Zhang J S, Jin Y J, *et al.* Adsorption of Pb(II), Cd(II) and Zn(II) by extracellular polymeric substances extracted from aerobic granular sludge: efficiency of protein[J]. *Journal of Environmental Chemical Engineering*, 2015, **3**(2): 1223-1232.
- [4] Jang H M, Ha J H, Park J M, *et al.* Comprehensive microbial analysis of combined mesophilic anaerobic-thermophilic aerobic process treating high-strength food wastewater [J]. *Water Research*, 2015, **73**: 291-303.
- [5] Franca R D G, Vieira A, Mata A M T, *et al.* Effect of an azo dye on the performance of an aerobic granular sludge sequencing batch reactor treating a simulated textile wastewater[J]. *Water Research*, 2015, **85**: 327-336.
- [6] 王迪, 杨凤林, 周军, 等. 碳源对好氧颗粒污泥物理性状及除磷性能的影响[J]. *中国给水排水*, 2007, **23**(5): 85-89.  
Wang D, Yang F L, Zhou J, *et al.* Influence of carbon source on physical characteristics and phosphorus removal performance of aerobic granular sludge[J]. *China Water & Wastewater*, 2007, **23**(5): 85-89.
- [7] Fortela D L, Hernandez R, French W T, *et al.* Extent of inhibition and utilization of volatile fatty acids as carbon sources for activated sludge microbial consortia dedicated for biodiesel production[J]. *Renewable Energy*, 2016, **96**: 11-19.
- [8] 王芳, 于汉英, 张兴文, 等. 进水碳源对好氧颗粒污泥特性的影响[J]. *环境科学研究*, 2005, **18**(2): 84-88.  
Wang F, Yu H Y, Zhang X W, *et al.* Influence of carbon source on the characteristics of aerobic granules [J]. *Research of Environmental Sciences*, 2005, **18**(2): 84-88.
- [9] 高景峰, 陈冉妮, 苏凯, 等. 同步脱氮除磷好氧颗粒污泥形成与反应机制的研究[J]. *环境科学*, 2010, **31**(4): 1021-1029.
- Gao J F, Chen R N, Su K, *et al.* Formation and reaction mechanism of simultaneous nitrogen and phosphorus removal by aerobic granular sludge [J]. *Environmental Science*, 2010, **31**(4): 1021-1029.
- [10] Jeon C O, Park J M. Enhanced biological phosphorus removal in a sequencing batch reactor supplied with glucose as a sole carbon source [J]. *Water Research*, 2000, **34**(7): 2160-2170.
- [11] 罗冠. 碳源对静置/好氧/缺氧SBR(SOA-SBR)脱氮除磷性能的影响[D]. 长沙: 湖南大学, 2014. 34-37.
- [12] 卢文健, 杨殿海, 郭云, 等. 聚磷菌的快速富集及其除磷特性研究[J]. *环境污染与防治*, 2012, **34**(6): 31-36.  
Lu W J, Yang D H, Guo Y, *et al.* Rapid enrichment of polyphosphate accumulating organisms and its characteristics of phosphorus removal [J]. *Environmental Pollution and Control*, 2012, **34**(6): 31-36.
- [13] Henriot O, Meunier C, Henry P, *et al.* Improving phosphorus removal in aerobic granular sludge processes through selective microbial management [J]. *Bioresource Technology*, 2016, **211**: 298-306.
- [14] Zengin G E, Artan N, Orhon D, *et al.* Population dynamics in a sequencing batch reactor fed with glucose and operated for enhanced biological phosphorus removal [J]. *Bioresource Technology*, 2010, **101**(11): 4000-4005.
- [15] Cech J S, Hartman P. Glucose induced break down of enhanced biological phosphate removal [J]. *Environmental Technology*, 1990, **11**(7): 651-656.
- [16] 张兰河, 李德生, 王旭明, 等. 不同温度下碳源对AOA-SBR工艺PAO与GAO竞争释磷的影响[J]. *硅酸盐通报*, 2015, **34**(8): 2274-2280.  
Zhang L H, Li D S, Wang X M, *et al.* Effect of carbon sources on the competition about phosphorus release between PAO and GAO by AOA-SBR process under different temperature [J]. *Bulletin of the Chinese Ceramic Society*, 2015, **34**(8): 2274-2280.
- [17] 彭永臻, 薛桂松, 苗志加, 等. 葡萄糖为碳源的EBPR长期运行效果及聚磷菌的富集培养[J]. *东南大学学报(自然科学版)*, 2013, **43**(1): 136-141.  
Peng Y Z, Xue G S, Miao Z J, *et al.* Long term effect of glucose as sole carbon source on EBPR and PAOs enrichment [J]. *Journal of Southeast University (Natural Science Edition)*, 2013, **43**(1): 136-141.
- [18] She Z L, Zhao L T, Zhang X L, *et al.* Partial nitrification and denitrification in a sequencing batch reactor treating high-salinity wastewater [J]. *Chemical Engineering Journal*, 2016, **288**: 207-215.
- [19] 赵庆彬, 毕学军, 臧海龙, 等. 不同碳源对活性污泥反硝化能力的影响研究[J]. *环境工程*, 2013, **31**(5): 127-131.  
Zhao Q B, Bi X J, Zang H L, *et al.* Effect of different carbon-sources on denitrification of the activated sludge system [J]. *Environmental Engineering*, 2013, **31**(5): 127-131.
- [20] 杨碧印. 不同外加碳源反硝化生物滤池的深度脱氮研究[D]. 长沙: 湖南大学, 2015. 27-29.
- [21] Ye F X, Peng G, Li Y. Influences of influent carbon source on extracellular polymeric substances (EPS) and physicochemical properties of activated sludge [J]. *Chemosphere*, 2011, **84**(9): 1250-1255.

- [22] 刘亚男, 于水利, 赵冰洁, 等. 胞外聚合物对生物除磷效果影响研究[J]. 哈尔滨工业大学学报, 2005, **37**(5): 623-625.  
Liu Y N, Yu S L, Zhao B J, *et al.* Study on the role of extracellular exopolymers in biological phosphorus removal[J]. Journal of Harbin Institute of Technology, 2005, **37**(5): 623-625.
- [23] 李冬, 吴青, 梁瑜海, 等. 不同基质条件对亚硝化污泥胞外聚合物的影响[J]. 哈尔滨工业大学学报, 2015, **47**(4): 81-86.  
Li D, Wu Q, Liang Y H, *et al.* Effect of substrate concentration and type on the content of extracellular polymeric substances in the nitrification sludge [J]. Journal of Harbin Institute of Technology, 2015, **47**(4): 81-86.
- [24] 王景峰, 王暄, 季民, 等. A/O SBR 中同步硝化反硝化除磷颗粒污泥的富集[J]. 中国给水排水, 2006, **22**(17): 100-104.  
Wang J F, Wang X, Ji M, *et al.* Enrichment of granular sludge for simultaneous nitrification, denitrification and phosphorus removal in anaerobic-aerobic SBR [J]. China Water & Wastewater, 2006, **22**(17): 100-104.
- [25] Huang W L, Cai W, Huang H, *et al.* Identification of inorganic and organic species of phosphorus and its bio-availability in nitrifying aerobic granular sludge [J]. Water Research, 2015, **68**: 423-431.
- [26] Xie C S, Zhao J, Tang J, *et al.* The phosphorus fractions and alkaline phosphatase activities in sludge [J]. Bioresource Technology, 2011, **102**(3): 2455-2461.
- [27] Frølund B, Palmgren R, Keiding K, *et al.* Extraction of extracellular polymers from activated sludge using a cation exchange resin [J]. Water Research, 1996, **30**(8): 1749-1758.
- [28] Frølund B, Griebe T, Nielsen P H. Enzymatic activity in the activated-sludge floc matrix [J]. Applied Microbiology and Biotechnology, 1995, **43**(4): 755-761.
- [29] 国家环境保护总局. 水和废水监测分析方法[M]. (第四版). 北京: 中国环境科学出版社, 2002.
- [30] Liu W T, Nakamura K, Matsuo T, *et al.* Internal energy-based competition between polyphosphate-and glycogen-accumulating bacteria in biological phosphorus removal reactors-Effect of P/C feeding ratio[J]. Water Research, 1997, **31**(6): 1430-1438.
- [31] Liu W T, Mino T, Nakamura K, *et al.* Glycogen accumulating population and its anaerobic substrate uptake in anaerobic-aerobic activated sludge without biological phosphorus removal [J]. Water Research, 1996, **30**(1): 75-82.
- [32] Beer M, Stratton H M, Griffiths P C, *et al.* Which are the polyphosphate accumulating organisms in full-scale activated sludge enhanced biological phosphate removal systems in Australia? [J]. Journal of Applied Microbiology, 2006, **100**(2): 233-243.
- [33] Wang R D, Peng Y Z, Cheng Z L, *et al.* Understanding the role of extracellular polymeric substances in an enhanced biological phosphorus removal granular sludge system [J]. Bioresource Technology, 2014, **169**: 307-312.
- [34] 赵玉芬, 赵国辉, 麻远. 磷与生命化学[M]. 北京: 清华大学出版社, 2005.
- [35] Medeiros J J G, Cid B P, Gómez E F. Analytical phosphorus fractionation in sewage sludge and sediment samples [J]. Analytical and Bioanalytical Chemistry, 2005, **381**(4): 873-878.
- [36] Basuvaraj M, Fein J, Liss S N. Protein and polysaccharide content of tightly and loosely bound extracellular polymeric substances and the development of a granular activated sludge floc [J]. Water Research, 2015, **82**: 104-117.
- [37] Yan L L, Zhang S L, Hao G X, *et al.* Simultaneous nitrification and denitrification by EPSs in aerobic granular sludge enhanced nitrogen removal of ammonium-nitrogen-rich wastewater [J]. Bioresource Technology, 2016, **202**: 101-106.
- [38] Zhu L, Zhou J H, Lv M L, *et al.* Specific component comparison of extracellular polymeric substances (EPS) in flocs and granular sludge using EEM and SDS-PAGE [J]. Chemosphere, 2015, **121**: 26-32.
- [39] Geyik A G, Çeçen F. Variations in extracellular polymeric substances (EPS) during adaptation of activated sludges to new feeding conditions [J]. International Biodeterioration & Biodegradation, 2015, **105**: 137-145.

## CONTENTS

Comparison of Models on Spatial Variation of PM <sub>2.5</sub> Concentration; A Case of Beijing-Tianjin-Hebei Region .....	WU Jian-sheng, WANG Xi, LI Jia-cheng, <i>et al.</i> (2191)
Change of Atmospheric Pollution Diffusion Conditions in Beijing in Recent 35 Years .....	GUO Chun-wei, SUN Zhao-bin, LI Zi-ming, <i>et al.</i> (2202)
Precipitation and Its Effects on Atmospheric Pollutants in a Representative Region of Beijing in Summer .....	HAN Li-hui, ZHANG Hai-liang, XIANG Xin, <i>et al.</i> (2211)
Impact of Mountain-Valley Wind Circulation on Typical Cases of Air Pollution in Beijing .....	DONG Qun, ZHAO Pu-sheng, WANG Ying-chun, <i>et al.</i> (2218)
Fugitive Dust Emission Characteristics from Building Construction Sites of Beijing .....	XUE Yi-feng, ZHOU Zhen, HUANG Yu-hu, <i>et al.</i> (2231)
Characteristics of Volatile Organic Compounds Emitted from Biomass-pellets-fired Boilers .....	WU Chang-da, ZHANG Chun-lin, BAI Li, <i>et al.</i> (2238)
Effect of VOCs on O <sub>3</sub> and SOA Formation Potential During the Combined Pollution Process in Guangzhou Panyu Atmospheric Composition Station .....	ZOU Yu, DENG Xue-jiao, LI Fei, <i>et al.</i> (2246)
Characteristic Study on the "Weekend Effect" of Atmospheric O <sub>3</sub> in Northern Suburb of Nanjing .....	WANG Jun-xiu, AN Jun-lin, SHAO Ping, <i>et al.</i> (2256)
Atmospheric Ammonia/Ammonium-nitrogen Concentrations and Wet and Dry Deposition Rates in a Double Rice Region in Subtropical China .....	WANG Jie-fei, ZHU Xiao, SHEN Jian-lin, <i>et al.</i> (2264)
Species of Iron in Size-resolved Particle Emitted from Xuanwei Coal Combustion and Their Oxidative Potential .....	WANG Qiang-xiang, TAN Zheng-ying, ZHAO Hui, <i>et al.</i> (2273)
Dioxin Pollution and Occupational Inhalation Exposure of PCDD/Fs in Municipal Solid Waste Incinerator .....	DU Guo-yong, WANG Qian, ZHANG Shu-lin, <i>et al.</i> (2280)
Characteristics of Mercury Emissions from Modern Dry Processing Cement Plants in Chongqing .....	ZHANG Cheng, ZHANG Ya-hui, WANG Yong-min, <i>et al.</i> (2287)
Correlations of Light-duty Gasoline Vehicle Emissions Based on VMAS and CVS Measurement Systems .....	WANG Hong-yu, HUANG Cheng, HU Qing-yao, <i>et al.</i> (2294)
Emission Characteristics of Particulate Matter from Diesel Buses Meeting Different China Emission Standards Fueled with Biodiesel .....	LOU Di-ming, ZHAO Cheng-zhi, XU Ning, <i>et al.</i> (2301)
Spatial Variation and Environmental Significance of δ <sup>18</sup> O and δD Isotope Composition in Xijiang River .....	XU Qi, LI Jian-hong, SUN Ping-an, <i>et al.</i> (2308)
Comparative Study of SWAT and DNDC Applied to N Leach and Export from Subtropical Watershed .....	HAN Ning, CHEN Wei-liang, GAO Yang, <i>et al.</i> (2317)
Comparison of Relationship Between Conduction and Algal Bloom in Pengxi River and Modao River in Three Gorges Reservoir .....	JIANG Wei, ZHOU Chuan, JI Dao-bin, <i>et al.</i> (2326)
Temporal and Spatial Variation Characteristics of Nitrogen and Phosphorus in Sediment Pore Water and Overlying Water of Dianchi Caohai Lake .....	WANG Yi-ru, WANG Sheng-ru, JIAO Li-xin, <i>et al.</i> (2336)
Distribution and Emission Flux Estimation of Phosphorus in the Sediment and Interstitial Water of Xiangxi River .....	LUO Yu-hong, NIE Xiao-qian, LI Xiao-ling, <i>et al.</i> (2345)
Pollution Characteristics and Risk Assessment of Heavy Metals in Water and Sediment from Daye Lake .....	ZHANG Jia-quan, TIAN Qian, XU Da-mao, <i>et al.</i> (2355)
Formation of Brominated Disinfection By-products in Low Temperature Multi-effect Distillation (LT-MED) Process for Seawater Desalination .....	QI Fei, SUN Ying-xue, YANG Zhe, <i>et al.</i> (2364)
Applicability Comparison and Application Study of Two Methods for Determination of the Copper Complexing Capacity of Waters .....	WANG Chen-ye, JIANG Kuo, XIE Wen-long, <i>et al.</i> (2373)
Performance of Applying Scale Permeable Pavements for Control of Runoff Pollution in an Area with High Groundwater Level .....	JIN Jian-rong, LI Tian, SHI Zhen-bao (2379)
Removal of 2,4-dichlorophenol in Underground Water by Stabilized Nano Zero-valent Iron .....	ZHANG Yong-xiang, CHANG Shan, LI Fei, <i>et al.</i> (2385)
Enhancement of Sulfamerazine Degradation Under H <sub>2</sub> O <sub>2</sub> /KI System by Ultrasound and UVA Irradiation .....	WEI Hong, SUN Bo-cheng, YANG Xiao-yu, <i>et al.</i> (2393)
Comparison of Phosphate Adsorption onto Zirconium-Modified Bentonites with Different Zirconium Loading Levels .....	JINAG Bo-hui, LIN Jian-wei, ZHAN Yan-hui, <i>et al.</i> (2400)
Removal of Nitrogen in Municipal Secondary Effluent by a Vertical Flow Constructed Wetland Associated with Iron-carbon Internal Electrolysis .....	ZHENG Xiao-ying, ZHU Xing, ZHOU Xiang, <i>et al.</i> (2412)
Purification Efficiency and Influencing Factors of Combined Bio-filters for Aquaculture Wastewater .....	ZHANG Shi-yang, ZHANG Sheng-hua, ZHANG Xiang-ling, <i>et al.</i> (2419)
Effect of Temperature on PAO Activity and Substrate Competition .....	ZHANG Ling, PENG Dang-cong, CHANG Die (2429)
Enrichment and Nitrogen Removal Characteristics of Marine Anaerobic Ammonium Oxidizing Bacteria .....	FENG Li, YU De-shuang, LI Jin, <i>et al.</i> (2435)
Ammonia Removal Rate and Microbial Community Structures in Different Biofilters for Treating Aquaculture Wastewater .....	ZHOU Hong-yu, HAN Mei-lin, QIU Tian-lei, <i>et al.</i> (2444)
Influence of Phosphate on Nitrogen Removal Efficiency of ANAMMOX Sludge .....	ZHOU Zheng, LIU Kai, WANG Fan, <i>et al.</i> (2453)
Characteristics and Mechanism of Biological Nitrogen and Phosphorus Removal Granular Sludge Under Carbon Source Stress .....	QIN Shi-you, CHEN Wei, MA Zhao-ni, <i>et al.</i> (2461)
Evolution of Extracellular Polymeric Substances of the Activated Sludge with Calcium Ion Addition During Set-up Period of Sequencing Batch Reactors .....	REN Li-fei, YANG Xin-ping, ZHANG Wen-wen (2470)
Isolation, Identification and Characterization of the Filamentous Microorganisms from Bulking Sludge .....	ZHANG Chong-miao, NIU Quan-ru, XU Li-mei, <i>et al.</i> (2477)
Applicability and Microbial Community Structure of Denitrification Suspended Carriers .....	TAN Yang, LI Ji, XU Qiao, <i>et al.</i> (2486)
Effect of Thiosulfate on the Carbon Fixation Capability of <i>Thiobacillus thioparus</i> and Its Mechanism .....	LI Huan, WANG Lei, WANG Ya-nan (2496)
Characteristics of Fungi Community Structure and Genetic Diversity of Forests in Guandi Mountains .....	QIAO Sha-sha, ZHOU Yong-na, CHAI Bao-feng, <i>et al.</i> (2502)
Source Apportionment of Soil Heavy Metals in City Residential Areas Based on the Receptor Model and Geostatistics .....	CHEN Xiu-duan, LU Xin-wei (2513)
Environmental Health Risk Assessment of Contaminated Soil Based on Monte Carlo Method; A Case of PAHs .....	TONG Rui-peng, YANG Xiao-yi (2522)
Influencing Mechanism of Eh, pH and Iron on the Release of Arsenic in Paddy Soil .....	ZHONG Song-xiong, YIN Guang-cai, CHEN Zhi-liang, <i>et al.</i> (2530)
Correlations Between Different Extractable Cadmium Levels in Typical Soils and Cadmium Accumulation in Rice .....	CHEN Qi, DENG Xiao, CHEN Shan, <i>et al.</i> (2538)
Remedying Effects of a Combined Amendment for Paddy Soil Polluted with Cd for Spring and Autumn Rice .....	CHEN Li-wei, YANG Wen-tao, GU Jiao-feng, <i>et al.</i> (2546)
Effects of Two Amendments on Remedying Garden Soil Complexly Contaminated with Pb, Cd and As .....	TIAN Tao, LEI Ming, ZHOU Hang, <i>et al.</i> (2553)
Sorption of Phenanthrene to Soybean and Wheat Roots and the Bioavailability of Sorbed Phenanthrene .....	WANG Hong-ju, LI Qian-qian, SHEN Yu, <i>et al.</i> (2561)
Effects of Dissolved Organic Matter Fractions Extracted from Humus Soil on Sorption of Benzotriazole in Brown Soil and Black Soil .....	YANG Ning-wei, BI Er-ping (2568)
Effects of Topography, Tree Species and Soil Properties on Soil Enzyme Activity in Karst Regions .....	LUO Pan, CHEN Hao, XIAO Kong-cao, <i>et al.</i> (2577)
Effects of Long-term Organic Amendments on Soil N <sub>2</sub> O Emissions from Winter Wheat-maize Cropping Systems in the Guanzhong Plain .....	HAO Yao-xu, LIU Ji-xuan, YUAN Meng-xuan, <i>et al.</i> (2586)
Exposure Route of Dioxin-like Polychlorinated Biphenyls in Hair Based on Passive Sampling .....	YUAN Hao-dong, BAI Yao, LI Qiu-xu, <i>et al.</i> (2594)
Accumulation Characteristics and Health Risk Assessment of Heavy Metals in Wild Fish Species from Diaojiang River, Guangxi .....	WANG Jun-neng, MA Peng-cheng, ZHANG Li-juan, <i>et al.</i> (2600)
Effect of Activated Carbon Addition on the Anaerobic Fermentation of Corn Straw in Mesophilic and Thermophilic Conditions .....	GAN Rong, GE Ming-min, LIU Yong-di, <i>et al.</i> (2607)
Volatile Organic Compounds (VOCs) Source Profiles of Industrial Processing and Solvent Use Emissions; A Review .....	WANG Hong-li, YANG Zhao-xun, JING Sheng-ao (2617)