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目次

PM _{2.5} 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 _{2.5} 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,沈雨冉,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 ₃ 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,王青曜,米持真一,吕森林(2273)
垃圾焚烧厂区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)
西江水氢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,胥焘,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	王晨烨,姜括,谢文龙,汪磊(2373)
高地下水位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 ₂ O ₂ /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,周橄(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 ²⁺ 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,王陇梅,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和铁对水稻土钾释放的影响机制	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 ₂ 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,吴夏荒,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)
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组合生物滤池对养殖废水的净化效率及影响因素分析

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摘要: 生物滤池作为一种有效的污水处理技术, 已有广泛应用. 但是关于组合生物滤池净化效能与影响因素系统分析仍然缺乏报道. 为此, 设计构建了曝气垂直流滤池 + 折流式水平流滤池的组合系统, 通过设定不同的水力负荷 (131、94、60 mm·d⁻¹) 及分流比 (8:2、6:4、4:6) 来探究运行工况的调整对组合系统净化效能的影响. 结果表明, 曝气垂直流滤池对有机物、氨氮及溶解性氮的平均去除率在 80% 以上, 而折流式水平流滤池对氨氮、总氮及溶解性氮的平均去除率在 40% 以下. 不同运行工况对生物滤池的净化效能存在显著影响, 且两种不同类型滤池的净化效能也存在显著差异 ($P < 0.05$). 氧化分解是两种滤池中有机物去除的主要途径之一. 两种滤池内都存在明显的硝化-反硝化, 它们是滤池去除总氮的主要途径. 垂直流滤池内的硝化-反硝化强度都高于水平流滤池. 磷的去除主要受控于水力负荷、温度、溶解氧、有机物等, 表明微生物吸收是滤池除磷的主要方式之一. 相比于单一垂直流滤池, 组合系统对总有机物和总磷的去除分别提高了 4.4% 和 23.2%, 对总氮的去除却降低了 12.1%. 降低分流比有助于提升水平流滤池反硝化强度, 但是由于从原水中引入过多的氨氮, 又水平流滤池的硝化能力有限, 进而导致组合系统总氮去除率下降. 因此, 根据处理原水组成, 控制适宜的分流比、停留时间及滤池内的氧化还原条件是提升该组合系统整体净化效果的关键.

关键词: 曝气垂直流滤池; 折流式水平流滤池; 水力负荷; 分流比; 去除效率; 组合系统

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Purification Efficiency and Influencing Factors of Combined Bio-filters for Aquaculture Wastewater

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Abstract: As an effective technology for wastewater treatment, bio-filter has been widely used. Nevertheless, there is still a lack of systematic report on purification efficiency and influencing factors of combined bio-filters. To this end, a novel combined system that consisted of aerated vertical-flow filter (AVF) followed by baffled horizontal-flow filter (BHF) was designed. After setting a series of hydraulic loading rates (131, 94 and 60 mm·d⁻¹) and diversion ratios (8:2, 6:4, 4:6), we comprehensively assessed the impact of running condition adjustment on treatment performance by multiple statistical analyses. The results showed that, the average removal rates of organic matter, ammonia nitrogen and dissolved nitrogen in AVF were all above 80%, while the average removal rates of ammonia nitrogen, total nitrogen and dissolved nitrogen in BHF were all below 40%. Different running conditions had a significant ($P < 0.05$) impact on treatment performance. Meanwhile, there were significant differences in purification efficiency between the two different kinds of filters. Oxidative degradation was one of the main ways to remove organic matter in the two kinds of filters. There were obvious nitrification and denitrification processes within the two kinds of filters. Nitrification followed by denitrification was the main way to remove total nitrogen since ammonium occupied the most portion of total nitrogen in the synthetic wastewater. Meanwhile, the intensity of nitrification and denitrification in AVF was obviously higher than that in BHF. Phosphorus removal was mainly controlled by hydraulic loading rate, temperature, dissolved oxygen, organic matter, etc. This might indicate that microbial absorption was one of the main ways to remove phosphorus for the two filters. Compared to the sole AVF, the removal of total organic matter and total phosphorus in the combined system was increased by 4.4% and 23.2%, respectively, but the removal of total nitrogen was reduced by 12.1%. Reducing the diversion ratio was helpful to improve the denitrification intensity in BHF. However, due to the introduction of excessive ammonia from the raw wastewater, as well as the limited nitrification capacity in BHF, the removal rate of total nitrogen for the combined system was decreased. Therefore, according to the composition of treated raw wastewater, the control of appropriate diversion ratio, residence time and redox conditions inside the filter bed was the key to enhance the overall performance of

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the combined system.

Key words: aerated vertical-flow filter; baffled horizontal-flow filter; hydraulic loading rate; diversion ratio; removal efficiency; combined system

生物滤池作为生物膜反应器的经典形式之一,已经成为一种成熟的工艺.近年来,伴随各种新型脱氮途径的提出,如异养硝化、好氧反硝化、同步硝化-反硝化、短程硝化-反硝化等,研究者们将传统生物滤池不断进行改进,开发出许多新型生物滤池,并在各类废水处理中得到了应用^[1~5].然而,这些新型生物滤池仍然缺乏设计经验,且无详细明确的工艺设计准则.生物脱氮是去除氮素的主要途径之一.强化生物脱氮的关键在于调控系统内部的氧化还原条件及优化原水中有有机碳源的利用^[2,5,6],而且系统的水力停留时间、反应温度、进水理化特征等也都与脱氮效率密切相关^[7,8].

水产养殖废水通常富含氮、磷、有机物等,极易对地表水造成富营养化^[9].削减养殖废水氮磷排放、开发适宜处理技术、提高水资源使用效率已成为我国发展生态农业当务之急.鉴于此,作者设计了曝气垂直流滤池(aerated vertical-flow filter, AVF)+折流式水平流滤池(baffled horizontal-flow filter, BHF)的组合系统,将前者的强硝化功能与后者的优势反硝化功能有机结合^[10].同时,通过设计不同的水力负荷及分流比来分别调控系统的反应时间及对原水中碳源的利用,最终达到高效脱除养殖废水中氮磷、有机物的目的.本研究通过全面分析组合系统的净化效能与影响因素的关系,探究组合系统的净化机制,以期为该组合系统在养殖废水处理中的应用提供依据.

1 材料与方法

1.1 试验系统设计与构建

试验系统设计如下:配水池内原水经水泵抽提后通过分流阀(控制分流比)一部分流入曝气垂直流滤池,另一部分直接流入调节池,后者与曝气垂直流滤池底部出水混匀后再流入折流式水平流滤池(图1).分流的目的主要是补充后一级滤池反硝化所需的有机碳源.所有单元构筑材料均为有机玻璃,除调节池($L\ 20\ \text{cm} \times W\ 20\ \text{cm} \times H\ 30\ \text{cm}$)为圆柱形结构外,其它均为方形箱体.配水池与曝气垂直流滤池规格一致($L\ 48\ \text{cm} \times W\ 48\ \text{cm} \times H\ 60\ \text{cm}$).曝气垂直流滤池表面铺设PVC布水管,底部设有PVC集水管;集水管内设有纳米微孔曝气管,后者通过聚乙烯软管与旋涡风机相连(风量: $60\ \text{m}^3 \cdot \text{h}^{-1}$;

最大风压: $10\ \text{kPa}$;品牌:亚士霸;型号:HG-250;产地:浙江台州).折流式水平流滤池($L\ 100\ \text{cm} \times W\ 48\ \text{cm} \times H\ 48\ \text{cm}$)自进水端向出水端呈3‰坡度倾斜;同时,折流式水平流滤池内增设了9个等间距平行交错的有机玻璃折流板($L\ 39\ \text{cm} \times W\ 0.9\ \text{cm} \times H\ 48\ \text{cm}$).两组滤池内部均填充孔径3~5 mm的多孔陶粒,垂直流滤池填充深度38 cm,水平流滤池填充深度34 cm,陶粒孔隙率为0.433.

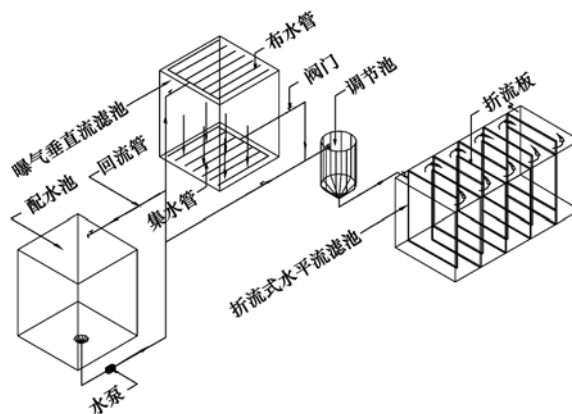


图1 组合系统结构示意图

Fig. 1 Schematic diagram of the combined system

1.2 滤池运行与数据采集

滤池的挂膜方式采用接种法,具体是在曝气垂直流滤池和折流式水平流滤池内分别接种采自某养殖场的活性污泥,每周接种一次,直至滤料表面均被生物膜覆盖为止^[11,12].挂膜结束后,将模拟配制的高质量浓度养殖废水接种至两组滤池内,进行微生物适宜性驯化,待系统出水水质稳定后,再进行数据采集.试验废水配置参考上述养殖场排放的高质量浓度养殖废水,配置方案如下:即每升水含面粉、葡萄糖(含少量钠、钙、铁、锌等元素)、碳酸氢铵、磷酸二氢钾的质量依次为0.287 5、0.144、0.054和0.022 g.配置废水对应各项污染物的质量浓度见表1.

测试过程按设定的分流比分为3个阶段,但不同阶段折流式水平流滤池的水力负荷不变(即各阶段总进水量恒定).所设定的3个分流比依次为8:2、6:4和4:6.以8:2为例进行说明:即曝气垂直流滤池底部出水量与调节池内未经处理的原水体积比为8:2.对应地,曝气垂直流滤池运行的3种水力负荷依次为 (131 ± 7) 、 (94 ± 7) 和 $(60 \pm 2)\ \text{mm} \cdot \text{d}^{-1}$.

表 1 试验模拟配置的废水组成¹⁾/mg·L⁻¹

Table 1 Composition of the simulated wastewater used for the experiment/mg·L⁻¹

水质指标	TCOD	DCOD	TP	IP	NH ₄ ⁺ -N	NO ₃ ⁻ -N	NO ₂ ⁻ -N	TN	DCOD/TN	Na	Ca	Fe	Zn
质量浓度	114±24	93±24	5.04±0.29	4.36±0.66	9.08±0.86	2.05±0.38	0.04±0.07	13.04±0.90	7.13	0.43±0.04	0.36±0.05	0.01±0.01	0.02±0.01

1) 数值表示为 mean ± SD

组合系统每天间歇进水一次,即曝气垂直流滤池水力停留时间为 24 h,折流式水平流滤池理论水力停留时间为 43.7 h. 曝气垂直流滤池每天曝气运行 4 h(10:00 ~ 14:00),对应气水比约为 1 200:1. 水样采集点为曝气垂直流滤池进水、底部出水,折流式水平流滤池进水、末端出水. 采样频率为每天 1 次,每次采样时间点固定(08:30 ~ 09:30);每种分流比持续采样 8 次,随后切换至下一分流比,继续运行 2 周待系统稳定后再进行下一轮数据采集. 采用美国 YSI 多参数水质分析仪(型号:Pro Plus)现场测定压强(p)、温度(T)、溶解氧(DO)、氧化还原电位(ORP)、碱度(pH)、电导率(Cond)、比电导率(SC)、总溶解固体(TDS)、盐度(Sal)、电阻(Res)等在线参数. 水样采集后,按国家标准方法^[13]测定 COD、TN、NO₃⁻-N、NO₂⁻-N、NH₄⁺-N、TP、IP 等指标,其中 COD 测量为锰法. COD 又分为总有机物(TCOD)和溶解性有机物(DCOD). DCOD 为水样经滤纸过滤后测定值,TCOD 为直接测定值.

1.3 数据分析

本文采用百分比去除率评价滤池的净化效能,即百分比去除率=(进水质量浓度-出水质量浓度)/进水质量浓度×100%. 独立样本 t -test 用于检验进出水间理化特征的差异及两种滤池间净化效能

的差异. 单因素方差分析(one-way ANOVA)用于检验不同水力负荷/分流比对滤池净化效能的影响,多重比较选择 LSD(方差齐)或 Games-Howell(方差不齐). 为了综合分析监测的所有理化因子对净化效率的影响,采用逐步回归分析及非线性冗余度分析(redundancy analysis, RDA)探讨污染物去除率与滤池进出水理化特征的关系. 因为监测的理化因子变量较多,为了避免变量之间的自相关,在进行 RDA 排序之前,先对监测的环境变量进行主成分分析. 这些分析在 SPSS 19.0 及 CANOCO 4.5 软件中完成.

2 结果与讨论

2.1 生物滤池进出水理化特征比较

比较两种不同类型的生物滤池进出水理化特征,发现曝气垂直流滤池、折流式水平流滤池进出水的压强、温度无显著差异,折流式水平流滤池进出水的氧化还原电位也无显著差异,其余监测指标差异显著. 进一步比较发现,曝气垂直流滤池的出水电阻率显著增加,而其它有差异的指标均显著降低;类似地,折流式水平流滤池出水电导率、比电导率、总溶解固体、盐度均显著增加,而其它有差异的指标显著降低(表 2).

表 2 两种生物滤池进出水理化参数比较¹⁾

Table 2 Comparison of physicochemical parameters between inflow and outflow of the two bio-filters

滤池类型	位点	压强/kPa	温度/℃	溶解氧/mg·L ⁻¹	氧化还原电位/mV	碱度 pH	电导率/mS·cm ⁻¹	比电导率/μS·cm ⁻¹	总溶解固体/g·L ⁻¹	盐度×10 ⁻⁶ /mol·L ⁻¹	电阻率/Ω
曝气垂直流滤池	进水	100.7±0.4	20.4±1.3	7.83±0.99	64±105	7.97±0.42	0.31±0.01	335±9	0.22±0.01	0.16±0.01	3269±112
	出水	100.7±0.4	20.3±1.4	2.09±0.53	-64±47	6.99±0.15	0.28±0.02	308±17	0.20±0.011	0.15±0.01	3 575±215
	P-value	1.000	0.732	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
折流式水平流滤池	进水	100.6±0.4	20.3±1.3	4.62±1.10	-62±69	7.20±0.14	0.29±0.01	319±10	0.21±0.01	0.15±0.00	3451±158
	出水	100.7±0.3	20.0±1.3	2.38±0.76	-86±48	7.00±0.16	0.31±0.03	345±43	0.22±0.0	0.16±0.02	3 241±295
	P-value	0.811	0.352	0.000	0.151	0.000	0.005	0.006	0.006	0.010	0.003

1) 黑体字表示进出水间存在显著差异的理化参数

2.2 生物滤池净化效能比较

不同运行工况(水力负荷/分流比)的调整对生物滤池的净化效能存在显著影响,且两种不同类型生物滤池的净化效能也存在显著差异($P < 0.05$). 就曝气垂直流滤池而言,不同水力负荷对亚硝氮的去除率无显著影响,对其它指标有显著影响;类似

地,在折流式水平流滤池中不同分流比对无机磷和亚硝氮的去除率无显著影响,对其它指标相反;针对组合系统,不同运行工况对总磷、氨氮及亚硝氮的去除率无显著影响,对其它指标相反. 除溶解性有机物和硝氮外,两种不同类型滤池对其它指标的净化效率都存在显著差异(表 3).

进一步比较发现,在曝气垂直流滤池中,有机物的去除率随水力负荷的降低先升高后降低,但无论总有机物还是溶解性有机物总体平均去除率都在80%以上. 磷的去除率随水力负荷的降低呈增加趋势. 氨氮、亚硝氮、总氮及溶解性氮去除率随水力负荷的变化趋势与有机物类似,而硝氮去除率随水力负荷的变化趋势与磷相似. 总体而言(不分水力负荷变化),曝气垂直流滤池对有机物、氨氮及溶解性氮的平均去除率都在80%以上,对磷、亚硝氮的去除率不高,尤其是后者平均去除率仅为11.5%(表4).

在折流式水平流滤池中,有机物的去除率随分流比的增加先升高后降低,且总体平均去除率都在

70%以上. 无机磷的去除率随分流比的变化趋势与有机物类似,亚硝氮的去除率先降低后升高. 亚硝氮的去除率变化很大且都为负值,表明出水呈现亚硝氮积累. 总磷、氨氮、硝氮、总氮及溶解性氮的去除率随分流比的增加而增加. 折流式水平流滤池对氨氮、总氮及溶解性氮的去除率不高,平均去除率都在40%以下. 在组合系统中,除亚硝氮外,其余各项指标的变化趋势与折流式水平流滤池类似. 在组合系统中亚硝氮去除率的变化趋势与曝气垂直流滤池类似. 此外,曝气垂直流滤池对总有机物、氨氮、亚硝氮、总氮及溶解性氮的去除率显著高于折流式水平流滤池,而总磷、无机磷的变化趋势与此相反(表3和4).

表3 两种生物滤池单体及组合体不同运行工况下百分比去除率的协方差分析结果(P 值)¹⁾

Table 3 Statistical results of covariance analysis of percent removal rates under different running conditions for the sole or combined system of the two bio-filters

项目	TCOD	DCOD	TP	IP	TAN	NO ₃ ⁻ -N	NO ₂ ⁻ -N	TN	DIN
不同水力负荷下的曝气垂直流滤池比较	0.009	0.008	0.034	0.007	0.009	0.000	0.215	0.011	0.032
不同分流比下的折流式水平流滤池比较	0.002	0.003	0.004	0.307	0.007	0.000	0.931	0.008	0.000
不同水力负荷/分流比下的组合系统	0.045	0.013	0.164	0.027	0.312	0.003	0.721	0.000	0.003
两种不同类型滤池的直接比较	0.044	0.101	0.002	0.000	0.000	0.239	0.024	0.000	0.000

1) 黑体字表示 P 值达显著($P < 0.05$)水平

表4 两种生物滤池单体及组合体不同运行工况下的百分比去除率比较¹⁾

Table 4 Comparison of percent removal rates under different running conditions for the single or combined system of the two bio-filters

类型	运行工况	TCOD	DCOD	TP	IP	TAN	NO ₃ ⁻ -N	NO ₂ ⁻ -N	TN	DIN
曝气垂直流滤池	1	72.0 ± 22.1 ^a	71.7 ± 22.2 ^a	32.6 ± 11.8 ^a	23.4 ± 31.3 ^a	83.8 ± 6.6 ^a	36.8 ± 28.2 ^a	-124.5 ± 457.1	62.3 ± 10.2 ^a	73.9 ± 9.9 ^a
	2	93.1 ± 2.6 ^b	93.0 ± 2.7 ^b	44.3 ± 6.6 ^b	52.7 ± 8.6 ^b	90.3 ± 3.0 ^b	54.0 ± 22.5 ^a	87.5 ± 10.8	76.1 ± 3.2 ^b	84.1 ± 3.4 ^b
	3	86.4 ± 4.6 ^b	86.3 ± 2.4 ^b	45.2 ± 11.4 ^b	53.8 ± 11.6 ^b	80.9 ± 7.3 ^a	92.6 ± 17.4 ^b	62.1 ± 31.2	69.9 ± 10.5 ^{ab}	82.8 ± 9.1 ^b
	总体	84.2 ± 15.2	84.0 ± 15.2	40.8 ± 11.3	43.7 ± 23.5	85.2 ± 6.9	60.9 ± 32.2	11.5 ± 265.4	69.7 ± 10.0	80.4 ± 8.8
折流式水平流滤池	1	48.4 ± 34.1 ^a	48.8 ± 39.0 ^a	45.0 ± 6.8 ^a	60.3 ± 12.4	19.5 ± 25.6 ^a	18.0 ± 25.6 ^a	-288.6 ± 524.1	33.4 ± 11.1 ^a	20.0 ± 18.5 ^a
	2	85.2 ± 7.0 ^b	88.9 ± 5.9 ^b	48.1 ± 4.1 ^a	69.1 ± 12.4	21.9 ± 22.0 ^a	45.0 ± 25.9 ^b	-331.4 ± 783.9	39.1 ± 4.6 ^a	25.9 ± 21.0 ^a
	3	80.8 ± 4.2 ^b	80.7 ± 2.3 ^b	57.0 ± 8.4 ^b	65.0 ± 9.4	51.3 ± 7.7 ^b	86.1 ± 7.5 ^c	-223.7 ± 337.6	47.3 ± 7.5 ^b	56.6 ± 5.5 ^b
	总体	72.0 ± 25.2	73.4 ± 27.7	50.0 ± 8.1	65.0 ± 11.7	30.6 ± 24.1	49.5 ± 34.9	-283.2 ± 565.9	39.9 ± 9.6	33.8 ± 22.7
组合系统	1	86.2 ± 6.3 ^a	83.6 ± 11.2 ^a	62.6 ± 3.3	72.7 ± 7.0 ^a	63.3 ± 6.3	31.6 ± 34.1 ^a	-576.3 ± 963.0	50.1 ± 3.2 ^a	56.4 ± 9.9 ^a
	2	91.8 ± 4.6 ^b	94.1 ± 3.4 ^b	63.1 ± 3.9	81.9 ± 8.0 ^b	66.2 ± 11.0	55.0 ± 34.7 ^a	-268.6 ± 801.5	60.0 ± 4.7 ^b	64.0 ± 9.3 ^a
	3	87.3 ± 1.8 ^{ab}	87.4 ± 1.4 ^{ab}	66.5 ± 5.5	77.4 ± 3.1 ^{ab}	69.4 ± 4.0	88.4 ± 15.1 ^b	-447.9 ± 515.4	62.3 ± 4.4 ^b	72.3 ± 2.2 ^b
	总体	88.6 ± 5.1	88.6 ± 7.8	64.0 ± 4.5	77.5 ± 7.3	66.3 ± 7.9	58.2 ± 36.8	-424.4 ± 761.0	57.6 ± 6.7	64.2 ± 10.0

1) 各运行工况之间不同字母标注表示存在显著差异; DIN = TAN + NO₂⁻-N + NO₃⁻-N. 曝气垂直流滤池运行工况1、2、3分别代表(131 ± 7)、(94 ± 7)和(60 ± 2) mm·d⁻¹这3种水力负荷;折流式水平流滤池1、2、3分别代表8:2、6:4和4:6这3种分流比;对应地,组合系统1、2、3分别代表上述运行工况组合

2.3 影响滤池净化效能因素分析

2.3.1 逐步回归分析

由逐步回归分析结果可知,在曝气垂直流滤池中溶解性有机物、亚硝氮与进水影响因素间无显著相关性;类似地,在折流式水平流滤池中亚硝氮与进水影响因素间无显著相关性. 除此之外,其余指标与两种滤池进出水影响因素间都存在显著的线性关系(表5).

针对进水理化特征,在曝气垂直流滤池中总有

有机物去除与温度成正比,可能原因是温度越高,越能促进微生物对有机物的氧化分解^[14]. 磷的去除与溶解氧正相关,可能原因是溶解氧含量越高,聚磷菌增殖愈快,进而对磷的吸收作用越强^[15,16]. 氨氮的去除与硝氮成反比,这是因为氨氮的去除主要是通过硝化作用,而进水硝氮含量越高对硝化作用有抑制作用^[17]. 此外,氨氮的去除还与氧化还原电位正相关,这是因为硝化作用强弱与氧化还原电位正相关. 总氮的去除与总有机物正相关,可能原因反硝

化脱氮需要碳源,有机物含量越高,越能促进反硝化强度^[6]。这种解释被随后的线性关系,即溶解性氮的去除与溶解性有机物正相关进一步验证(表 5)。

针对出水理化特征,在曝气垂直流滤池中各污染物的去除率主要取决于出水质量浓度,即出水质量浓度越高,去除率越低。总有机物的去除与溶解性氮负相关,这是因为出水溶解性氮含量越高,反硝化作用越弱;相应地,反硝化消耗的碳源也就越少。总有机物的去除与 pH 值负相关,这是因为反硝化作用释放碱度,pH 值升高能抑制反硝化作用^[17]。此外,总有机物的去除与溶解氧正相关,这是因为溶

解氧越高,越能促进有机物的氧化分解。溶解性有机物的去除也有类似规律,不过它还与盐度、硝氮、压强、亚硝氮等相关。总磷的去除与总溶解固体负相关,这可能是因为磷酸盐是总溶解固体的重要组份,出水总溶解固体含量愈高,磷的去除率愈低。硝氮的去除与氨氮正相关,这是因为出水氨氮含量愈高,通过硝化作用转化成硝氮的含量也就愈低。总氮的去除与氧化还原电位、pH 值负相关,这是因为总氮的去除主要依赖于反硝化过程,而反硝化倾向于厌氧环境且释放碱度^[17];亚硝氮的去除与 pH 值负相关也是类似原因(表 5)。

表 5 两种生物滤池百分比去除率与进出水影响因素间的逐步回归分析结果¹⁾

Table 5 Results of stepwise regression between percent removal rate and inflow/outflow influencing factors among the two bio-filters			
滤池类型	参数	标准化系数 R	显著水平 (Sig.)
曝气垂直流滤池	TCOD	$0.409 \times T$	0.043
	DCOD	ND	
	TP	$-0.439 \times \text{HLR} + 0.414 \times \text{DO} - 0.362 \times T + 0.355 \times \text{ORP} - 0.239 \times \text{NO}_3^- \text{-N}$	0.000
	IP	$0.461 \times \text{DO} - 0.365 \times T - 0.363 \times \text{HLR} + 0.361 \times \text{TCOD} - 0.215 \times \text{P} + 0.128 \times \text{ORP}$	0.000
	进水 TAN	$-0.464 \times \text{NO}_3^- \text{-N} + 0.335 \times \text{TDS} + 0.324 \times \text{ORP}$	0.000
	NO ₃ ⁻ -N	$0.590 \times \text{IP} - 0.474 \times \text{NO}_3^- \text{-N} - 0.458 \times \text{TDS} - 0.411 \times \text{NO}_2^- \text{-N}$	0.000
	NO ₂ ⁻ -N	ND	
	TN	$0.498 \times \text{TCOD} - 0.448 \times \text{NO}_3^- \text{-N}$	0.000
	DIN	$-0.701 \times \text{NO}_3^- \text{-N} + 0.435 \times \text{DCOD} - 0.211 \times \text{NO}_2^- \text{-N}$	0.000
	TCOD	$-0.950 \times \text{TCOD} - 0.152 \times \text{DIN} - 0.125 \times \text{pH} + 0.103 \times \text{DO}$	0.000
	DCOD	$-2.210 \times \text{DCOD} + 1.473 \times \text{TCOD} - 0.345 \times \text{DIN} + 0.198 \times \text{DO} - 0.198 \times \text{Sal} + 0.198 \times \text{NO}_3^- \text{-N} - 0.148 \times \text{P} - 0.060 \times \text{NO}_2^- \text{-N}$	0.000
	TP	$-0.804 \times \text{TP} - 0.223 \times \text{TDS}$	0.000
	IP	$-0.803 \times \text{IP} - 0.364 \times \text{NO}_3^- \text{-N}$	0.000
	出水 TAN	$-0.984 \times \text{TAN}$	0.000
折流式水平流滤池	NO ₃ ⁻ -N	$-0.983 \times \text{NO}_3^- \text{-N} + 0.179 \times \text{TAN}$	0.000
	NO ₂ ⁻ -N	$-0.734 \times \text{NO}_2^- \text{-N} - 0.301 \times \text{pH}$	0.000
	TN	$-0.917 \times \text{TN} - 0.157 \times \text{ORP} - 0.123 \times \text{pH}$	0.000
	DIN	$-0.989 \times \text{DIN}$	0.000
	TCOD	$0.904 \times \text{DCOD} - 0.474 \times \text{TAN} - 0.282 \times \text{P}$	0.000
	DCOD	$0.936 \times \text{DCOD} - 0.392 \times \text{TAN} - 0.223 \times \text{IP} - 0.212 \times \text{P}$	0.000
	TP	$0.800 \times \text{TP} + 0.289 \times \text{P}$	0.000
	IP	$0.513 \times \text{pH}$	0.009
	进水 TAN	$0.664 \times \text{DO} + 0.463 \times \text{TDS} + 0.313 \times \text{TAN} - 0.241 \times \text{P}$	0.000
	NO ₃ ⁻ -N	$0.496 \times \text{Ratio} - 0.464 \times \text{NO}_2^- \text{-N} + 0.439 \times \text{DCOD} - 0.206 \times \text{IP}$	0.000
	NO ₂ ⁻ -N	ND	
	TN	$1.264 \times \text{TN} - 0.998 \times \text{DIN} + 0.753 \times \text{TP} + 0.313 \times \text{Ratio} + 0.289 \times \text{ORP}$	0.000
	DIN	$0.867 \times \text{Ratio} + 0.449 \times \text{TDS} - 0.243 \times \text{P}$	0.000
	TCOD	$-0.701 \times \text{DIN} - 0.339 \times \text{DCOD}$	0.000
	DCOD	$-0.738 \times \text{DIN} - 0.544 \times \text{DCOD} + 0.324 \times \text{IP}$	0.000
出水	TP	$-0.688 \times \text{TP} - 0.392 \times \text{SC} + 0.282 \times T + 0.229 \times \text{DCOD}$	0.000
	IP	$-0.818 \times \text{IP} + 0.320 \times T$	0.000
	TAN	$-0.748 \times \text{DIN} + 0.631 \times \text{TN} - 0.408 \times \text{Sal} + 0.393 \times \text{DCOD}$	0.000
	NO ₃ ⁻ -N	$-0.648 \times \text{NO}_3^- \text{-N} + 0.600 \times \text{Ratio} + 0.306 \times \text{TN}$	0.000
	NO ₂ ⁻ -N	$-0.741 \times \text{NO}_2^- \text{-N}$	0.000
	TN	$-0.641 \times \text{SC}$	0.001
	DIN	$-0.755 \times \text{DIN}$	0.000

1) 用 SPSS 软件作逐步回归分析会给出标准化和非标准化系数。因为本研究监测的理化环境因子量纲不一致,为了更加合理地评价监测的每项环境因子对污染物去除效率的影响,采用标准化系数进行比较分析;ND 表示未检测到显著线性关系

针对进水理化特征,在折流式水平流滤池中有机的去除与进水溶解性有机物正相关,说明有机物的氧化分解是滤池脱除有机物的主要途径.这种假设被有机物的去除与氨氮的负相关进一步证实,即进水氨氮含量愈高,硝化作用与有机物分解竞争的溶解氧量也就愈高^[18].总磷的去除与进水负荷正相关,这与文献[3,19]报道的,在一定范围内污染物去除率随进水负荷呈线性递增一致.氨氮的去除与进水溶解氧正相关,说明硝化作用仍是氨氮去除的主要途径^[20].硝氮的去除与分流比、溶解性有机物正相关,与亚硝氮负相关,说明反硝化是硝氮去除的主要途径.总氮的去除与进水质量浓度、分流比正相关,与溶解性氮负相关,说明反硝化也是总氮去除的主要途径;此外,总氮的去除还与氧化还原电位正相关,说明在折流式水平流滤池内部还同时存在硝化作用^[17].溶解性氮与分流比正相关,说明反硝化是溶解性氮去除的主要途径^[21](表5).

针对出水理化特征,在折流式水平流滤池中多项污染物的去除率与出水质量浓度负相关,这与曝气垂直流滤池类似.有机物的去除与溶解性氮负相关,说明异养反硝化是有机物脱除的主要途径.总

磷的去除与温度、溶解性有机物正相关,可能是因为基质微生物在磷的吸附/吸收过程中起重要作用^[15,16,22,23],而微生物又与温度、有机物密切相关.氨氮的去除与溶解性氮负相关,可能是因为出水溶解性氮含量愈高,反硝化作用愈弱,致使积累的硝氮/亚硝氮抑制了氨氮的硝化过程^[17].氨氮的去除与总氮正相关,可能是因为系统倾向于好氧环境(出水平均溶解氧为 $2.38\text{ mg}\cdot\text{L}^{-1}$,表2),这有利于硝化过程而不利反硝化^[16],而总氮的去除主要依赖于反硝化.出水总氮含量愈高,意味反硝化愈弱,相反,好氧性愈强,愈利于氨氮的硝化过程.氨氮的去除还与溶解性有机物正相关,可能是因为出水溶解性有机物含量愈高,愈有利于反硝化过程,而硝氮/亚硝氮的减少又有利于氨氮向其转化^[17].此外,硝氮的去除与分流比正相关,说明反硝化是硝氮去除的主要途径(表5).

2.3.2 冗余度分析

在进行 RDA 排序之前,先对监测的 20 个进出水影响因素进行主成分分析.结果除折流式水平流滤池的进水理化特征提取到 4 个主成分外,其它 3 组都是提取到 5 个主成分,且每组主成分解释的累积方差都达到了 80% 以上(表6).

表 6 提取的主成分解释的累积方差

Table 6 Cumulative variance explained by the extracted components

主成分	曝气垂直流滤池进水	曝气垂直流滤池出水	折流式水平流滤池进水	折流式水平流滤池出水
1	26.3	35.7	25.1	31.8
2	47.6	55.1	49.2	47.7
3	63.9	66.3	69.5	60.6
4	76.0	77.5	83.6	72.7
5	83.1	87.3		83.5

由各主成分的因子载荷可知,针对曝气垂直流滤池进水理化特征,第一主成分主要包括磷、有机物、pH 值、溶解氧,第二、三主成分主要包括溶解性盐、温度、压强、水力负荷,第四主成分主要包括溶解性氮;针对曝气垂直流滤池出水理化特征,第一主成分主要包括溶解性盐、总氮,第二主成分主要包括有机物、溶解氧、pH 值,第三主成分包括压强、温度,第四主成分包括磷;类似地,针对折流式水平流滤池进水理化特征,第一主成分主要包括溶解性氮、总氮、溶解性盐,第二主成分主要包括溶解氧、分流比、有机物;针对折流式水平流滤池出水理化特征,第一主成分主要包括溶解性盐、氧化还原电位,第二主成分主要包括溶解性氮、分流比、总氮,第三主成分主要包括压强、温度、溶解氧、

pH 值(表7).

将从两种滤池各自进出水理化特征提取到的主成分与污染物的去除效率进行 RDA 排序分析,结果如图 2 所示.据 RDA 统计结果,监测的污染物去除效率与两种滤池各自进出水理化特征间均存在显著($P<0.05$)的线性关系,说明滤池对各种污染物的去除效率确实受控于监测的理化环境因子变异.

进一步分析排序图 2 发现,提取的各主成分对污染物的去除产生不同的影响.针对曝气垂直流滤池进水理化特征,溶解性氮、硝氮、总氮及磷的去除效率与第一主成分明显正相关,又结合表 7 因子载荷可知,该主成分主要由影响硝化-反硝化的碳源、溶解氧、碱度等因素构成.关于该正相关的解释为:溶解氧愈高,一方面愈有利于有机物的氧化

分解,另一方面愈有利于氨氮的硝化,产生更多的硝氮;又处理原水中不乏碳源(碳氮比为 7.13,表 1),加上滤池出水的低溶解氧环境(出水平均 DO: 2.09 mg·L⁻¹,表 2),更多的硝氮有利于提升反硝化强度^[10,24,25],进而提高溶解性氮和总氮的去除效率. 本研究中,处理原水中硝氮所占的比例较低(表 1),原水中较高的溶解氧在曝气停止后很快

被滤池内有机物的氧化分解和硝化过程消耗,进而进入厌氧状态,这有助于随后的反硝化过程. pH 值与溶解氧类似,因为硝化过程耗碱,pH 值愈高,愈有利于硝化过程^[17]. 磷的去除与上述因素正相关,可能是因为溶解氧、有机物含量愈高,愈能促进微生物增殖^[16],进而增强对磷的吸附/吸收强度[图 2(a)和表 7].

表 7 旋转主成分矩阵中各主成分的主要因子载荷¹⁾
Table 7 Major factor loadings for each component in rotated component matrix

项目	主成分				
	Factor_1	Factor_2	Factor_3	Factor_4	Factor_5
曝气垂直流滤池进水	0.940 (IP)	0.949 (SC)	0.955 (T)	0.808 (DIN)	0.896 (TN)
	0.918 (DCOD)	0.947 (TDS)	-0.859 (P)	-0.801 (NO ₂ ⁻ -N)	-0.573 (ORP)
	0.908 (TCOD)	0.810 (Sal)	-0.817 (Res)	0.690 (TAN)	
	0.876 (pH)	0.651 (HLR)	0.816 (Cond)	0.625 (NO ₃ ⁻ -N)	
	0.792 (DO)				
	0.655 (TP)				
曝气垂直流滤池出水	0.964 (TDS)	0.930 (TCOD)	0.811 (P)	0.839 (IP)	0.830 (NO ₃ ⁻ -N)
	0.962 (SC)	0.929 (DCOD)	-0.779 (T)	0.620 (TP)	0.677 (HLR)
	0.947 (TN)	-0.759 (DO)			
	0.869 (Cond)	0.748 (ORP)			
	0.862 (Sal)	-0.595 (pH)			
	-0.853 (Res)				
	0.819 (DIN)				
	0.710 (TAN)				
折流式水平流滤池进水	0.911 (DIN)	0.948 (DO)	0.810 (IP)	0.814 (P)	
	0.891 (TN)	0.913 (Ratio)	0.807 (TAN)	-0.753 (T)	
	0.778 (TDS)	0.897 (TCOD)	0.650 (pH)	0.717 (ORP)	
	0.771 (NO ₃ ⁻ -N)	0.884 (DCOD)	-0.589 (NO ₂ ⁻ -N)	0.635 (Res)	
	0.757 (SC)	0.601 (TP)		-0.577 (Cond)	
	0.731 (Sal)				
折流式水平流滤池出水	0.967 (Cond)	0.842 (DIN)	-0.804 (P)	0.704 (DCOD)	0.828 (IP)
	-0.947 (Res)	0.831 (NO ₃ ⁻ -N)	0.753 (T)	-0.697 (TP)	0.760 (TAN)
	0.945 (Sal)	-0.737 (Ratio)	0.705 (DO)	-0.650 (NO ₂ ⁻ -N)	0.484 (TCOD)
	0.945 (TDS)	0.580 (TN)	0.555 (pH)		
	0.944 (SC)				
	0.786 (ORP)				

1) 曝气垂直流滤池进水、出水理化特征作旋转主成分分析经 6 次迭代收敛;折流式水平流滤池进水、出水理化特征作旋转主成分分析经 8 次迭代收敛;提取方法:主成分分析;旋转方法: Kaiser 标准化最大方差法

针对曝气垂直流滤池出水理化特征,提取的各主成分与污染物去除效率均呈负相关. 除亚硝氮与第五主成分明显负相关外,其余指标与第一至第四主成分明显负相关. 亚硝氮与第五主成分明显负相关,这可能是因为出水硝氮含量愈高,暗示滤池内氧化性愈强,愈不利于反硝化过程. 这是因为亚硝氮为反硝化过程中间产物,极不稳定,很容易被氧化为硝氮^[17]. 在剩余指标中,有机物、氨氮、溶解性氮与第二、第三主成分明显负相关,可能是因为出水溶解氧、pH 值愈高,愈有利于硝化过程;出水中有机

物含量愈高,有机物氧化分解消耗的溶解氧也就愈多,留给氨氮硝化的溶解氧也就愈少^[26,27]. 氨氮的去除与温度正相关,这是因为温度愈高,滤池内部微生物的硝化反应强度愈烈^[16][图 2(b)和表 7].

针对折流式水平流滤池进水理化特征,无机磷与第三主成分明显正相关,亚硝氮与第四、第一主成分明显正相关,其余指标与第二主成分明显正相关. 氨氮、溶解性氮、总氮的去除与第二主成分正相关,可能是因为溶解氧愈高,伴随进水溶解氧的快速消耗,更多的氨氮被氧化成硝酸盐;与曝气垂直流

滤池类似,处理原水中不乏碳源,加上滤池内部的低溶解氧环境(出水平均 $\text{DO}: 2.38 \text{ mg} \cdot \text{L}^{-1}$, 表 2),反硝化强度提升,最终导致溶解性氮、总氮去除效率的提高^[28]. 溶解氧的提高也促进了有机物的氧化分解,提高了有机物的去除效率. 总磷的去除与溶解氧、有机物正相关同样归属于微生物代谢活动的增强[图 2(c)和表 7].

针对折流式水平流滤池出水理化特征,亚硝氮的去除与第四主成分明显正相关,与第三主成分明显负相关,磷的去除与第五主成分明显负相关,其余

指标与第一、第二主成分明显负相关. 亚硝氮的去除与溶解氧、碱度负相关,这是因为反硝化倾向于厌氧环境且释放碱度^[17],溶解氧和碱度的提升都不利于反硝化过程. 磷的去除与氨氮、总有机物负相关,可能是因为出水氨氮、有机物含量愈高,滤池内部的好氧微生物代谢活动也就愈弱,进而对磷的吸附/吸收活动也就愈弱. 总氮的去除与溶解性氮、硝氮负相关,与分流比、有机物的去除正相关,说明异养反硝化是滤池脱除总氮的主要形式[图 2(d)和表 7].

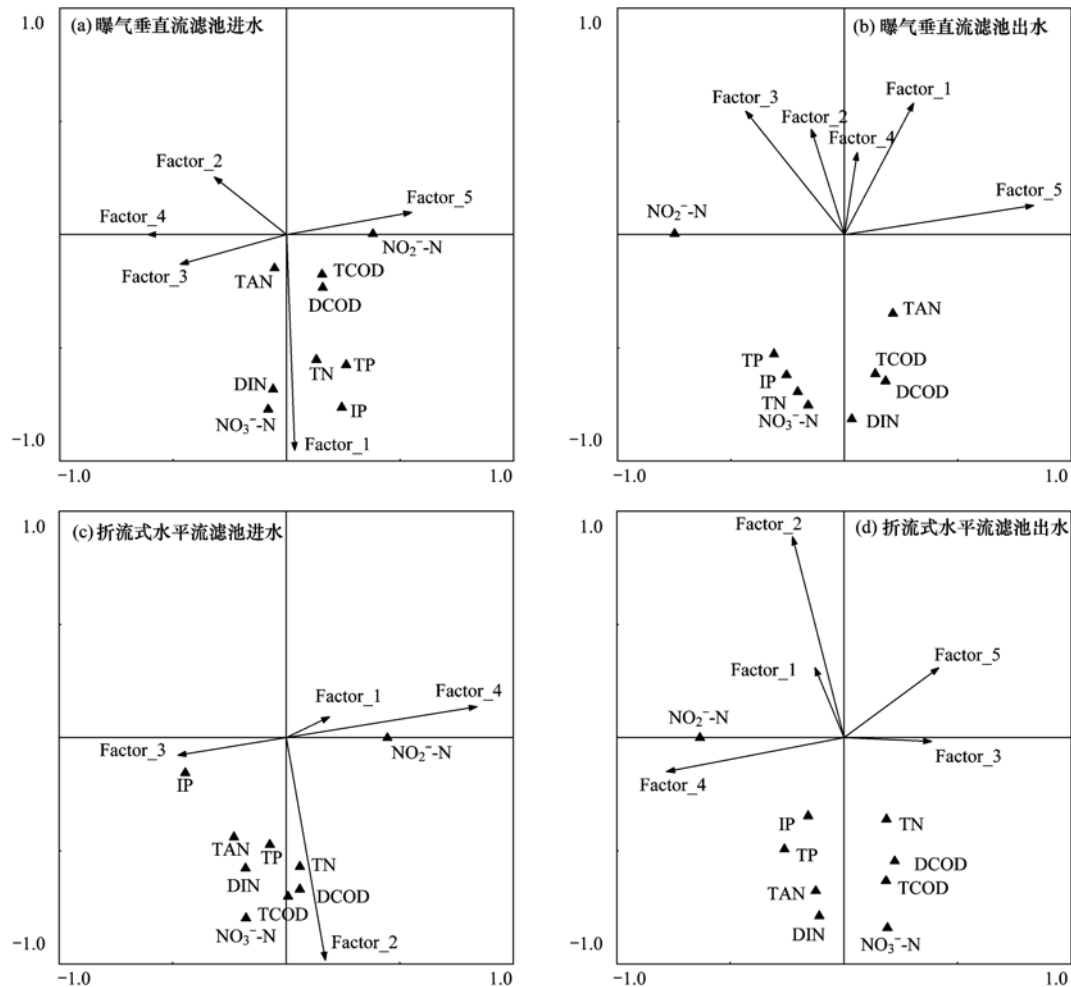


图 2 两种滤池百分比去除率与进出水影响因素间的冗余度分析排序

Fig. 2 Redundancy analysis (RDA) ordination plot based upon percent removal rate and influencing factors of inflow/outflow of the two bio-filters

3 结论

(1) 针对曝气垂直流滤池 + 折流式水平流滤池的组合系统,在好氧阶段,即滤池进水初期或曝气期水体中溶解氧含量较高,氧化分解是两种滤池内有机物去除的主要途径. 但是伴随溶解氧的快速消耗(如曝气垂直流滤池停止曝气后),两种滤池很快进

入缺氧或厌氧状态,随后异养反硝化形成了滤池内有机物减少的主要原因之一.

(2) 两种滤池内都存在明显的硝化-反硝化,且它们是滤池去除总氮的主要途径. 曝气垂直流滤池对氨氮及溶解性氮的平均去除率在 80% 以上,而折流式水平流滤池对氨氮及溶解性氮的平均去除率在 40% 以下,表明曝气垂直流滤池内的硝化-反硝化强

度都高于折流式水平流滤池。磷的去除主要受控于水力负荷、温度、溶解氧、有机物等,表明微生物吸收是滤池除磷的主要方式之一。

(3)相比于单一滤池,该组合系统提高了有机物和磷的去除效果,却降低了氮的去除效率。降低分流比有助于提升折流式水平流滤池反硝化强度,但是由于从原水中引入过多的氨氮,又折流式水平流滤池的硝化能力有限,进而导致组合系统总氮去除率下降。

(4)逐步回归及冗余度分析表明,滤池的净化效能不仅与运行工况、处理原水组成密切相关,同时还受控于运行的环境条件(溶解氧、温度等)。因此,根据处理原水组成,控制适宜的分流比、停留时间及滤池内的氧化还原条件是提升该组合系统整体净化效果的关键。

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CONTENTS

Comparison of Models on Spatial Variation of PM _{2.5} 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 ₃ 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 ₃ 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 ¹⁸ 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, <i>et al.</i> (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 ₂ O ₂ /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, <i>et al.</i> (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-nui, <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, <i>et al.</i> (2470)
Isolation, Identification and Characterization of the Filamentous Microorganisms from Bulking Sludge	ZHANG Chong-miao, NIU Quan-rui, 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, <i>et al.</i> (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, <i>et al.</i> (2513)
Environmental Health Risk Assessment of Contaminated Soil Based on Monte Carlo Method; A Case of PAHs	TONG Rui-peng, YANG Xiao-yi, <i>et al.</i> (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, <i>et al.</i> (2568)
Effects of Topography, Tree Species and Soil Properties on Soil Enzyme Activity in Karst Regions	LUO Pan, CHEN Hao, XIAO Kong-cai, <i>et al.</i> (2577)
Effects of Long-term Organic Amendments on Soil N ₂ 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, <i>et al.</i> (2617)