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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



2020

Vol.41 No.9
第41卷 第9期

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温度对城市污水厌氧生物滤池运行效果与菌群结构的影响

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摘要: 城市污水厌氧产甲烷是城市污水资源化利用途径之一, 但低有机物浓度和低温条件影响和限制该工艺在城市污水处理方面的应用。为此, 在中试反应器中对厌氧生物滤池处理实际城市污水的启动方式、不同温度条件下系统运行效果和菌群结构的变化进行了研究。结果表明, 采用间歇运行和连续运行相结合的挂膜方式, 可实现工艺的快速启动, 出水 SCOD 浓度稳定在 $60 \text{ mg} \cdot \text{L}^{-1}$ 。14℃ 以上厌氧生物滤池运行较稳定, 水解酸化菌和产甲烷菌代谢趋于平衡, 出水 SCOD 和 TCOD 浓度稳定在 $69 \text{ mg} \cdot \text{L}^{-1}$ 和 $90 \text{ mg} \cdot \text{L}^{-1}$ 。10℃ 低温条件下, 水解菌群相对丰度下降, 系统 TCOD 去除效果下降; 而消化链球菌科 (Peptostreptococcaceae) 产酸菌相对丰度增加至 32.79%, 导致系统出水 VFA 浓度从 $2 \text{ mg} \cdot \text{L}^{-1}$ 升高至 $12 \text{ mg} \cdot \text{L}^{-1}$; 产甲烷菌群数量略有降低, 产甲烷能力变化较小, 出水 SCOD 较为稳定。厌氧生物滤池生物膜菌群结构复杂, 菌群丰富度和多样性随温度的降低而下降。同时, 启动和温度降低过程中, 产甲烷菌群结构发生变化, 乙酸型产甲烷菌群丰度逐渐升高, 成为产甲烷优势菌群。因此, 城市污水厌氧生物滤池启动快, 能够抵抗温度持续降低的影响, 同时, 运行 9 个月不需反冲洗, 不存在易堵塞需频繁反冲洗的问题, 可更充分地发挥生物滤池的生物接触氧化和过滤截留的作用。

关键词: 城市污水; 生物滤池; 厌氧; 产甲烷; 中试

中图分类号: X172; X703.1 文献标识码: A 文章编号: 0250-3301(2020)09-4141-09 DOI: 10.13227/j.hjxx.202001014

Effect of Temperature on Performance and Microbial Community Structure of Anaerobic Biofilter-Treated Domestic Wastewater

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Abstract: Municipal wastewater methanogenesis is one of the ways to utilize municipal wastewater resources. In this study, a biofilter used to treat actual municipal wastewater was employed to investigate the methanogenesis in a pilot-scale reactor. The method of rapid start-up, the influence of temperature on the reactor performance, and the changes in the microbial structure were investigated in the pilot-scale study. The rapid start-up of the biofilter reactor was achieved by the combination of intermittent and continuous operations. The effluent concentration of SCOD was $60 \text{ mg} \cdot \text{L}^{-1}$ at the stable operation stage. The biofilter was operated steadily at a temperature higher than 14℃, the accumulation of volatile fatty acids (VFA) was low, and the effluent concentrations of SCOD and TCOD were $69 \text{ mg} \cdot \text{L}^{-1}$ and $90 \text{ mg} \cdot \text{L}^{-1}$, respectively. In addition, the metabolism of hydrolysis and methanogenesis tended to balance off under such conditions. However, the abundance of microorganisms that can hydrolyze organic matter and produce methane decreased. The abundance of Peptostreptococcaceae increased even the temperature was lower than 10℃, which typically increases VFA production. Therefore, the concentrations of effluent VFA and TCOD increased, but methane production decreased. The effluent concentration of SCOD was relatively stable. The microbial abundance and diversity were the richest at 19℃ in the reactor. The acetolactic methanogens were the dominant methanogens at low temperatures. The anaerobic biological filter for the treatment of urban sewage starts quickly and can resist the impact of continuous temperature reduction. Moreover, it does not need backwashing after running for nine months, and it is not easily clogged. Therefore, the functions of biological contact oxidation and filtration retention of the biological filter can be more fully utilized.

Key words: urban sewerage; biofilter; anaerobic; methane; pilot scale

目前, 城市污水中的有机物主要通过好氧氧化和反硝化两种方式去除。随着自养生物脱氮工艺的深入研究与应用^[1, 2], 自养脱氮工艺将不再需要大量有机物作为碳源进行反硝化, 但通过好氧方式去除城市污水中的有机物会消耗大量能源^[3]。厌氧处理工艺可将有机物转化成清洁能源甲烷, 该工艺具有能耗低、剩余污泥少和运行维护简单等优点^[4]。

城市污水的厌氧生物处理, 将促进污水处理由耗能向产能方向转变, 该方面研究已得到国内外学者的

收稿日期: 2020-01-02; 修订日期: 2020-03-15

基金项目: 国家自然科学基金项目(51878011); 北京市自然科学基金项目(8182012)

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关注.

目前,广泛研究的城市污水厌氧生物处理工艺有厌氧膜生物反应器(AnMBR)^[5]和上流式厌氧污泥床(UASB)^[6]. AnMBR 工艺处理效率较高,且具有良好的过滤作用;但该工艺抗冲击能力弱,且膜污染问题较严重,影响了该工艺的实际应用^[7]. UASB 工艺处理城市污水效果较好,但存在启动慢和难以维持颗粒化等问题^[8]. 厌氧菌生长缓慢,世代时间长,将厌氧生化反应与生物滤池相结合,既有利于充分发挥生物滤池截留过滤作用,保证厌氧菌长期停留在滤池中,又可避免因生物膜过度生长而导致的频繁反冲洗问题^[9]. 已有部分学者采用模拟城市污水在小试反应器中开展了厌氧生物滤池工艺的研究^[10,11],研究结果表明生物滤池可以实现城市污水的厌氧处理. 但是,到目前为止,有关实际城市污水厌氧生物滤池的中试研究未见报道.

温度是影响厌氧反应的关键因素,厌氧生化反应的最佳温度为 35℃^[12]. 但实际城市污水水温随季节变化,水温在 15~25℃ 之间. 研究城市污水中低温厌氧处理工艺更具实际意义,然而目前有关城市污水厌氧生物处理工艺的研究多将温度控制在 30~40℃^[13,14]. 杨忠启等^[15]采用厌氧生物滤池在 35℃ 条件下处理模拟生活污水, COD 的去除效果可达 75%. 有学者在 15~25℃ 条件下^[16],研究了 AnMBR 处理模拟城市污水的运行效果,当温度降至 15℃ 时, COD 去除率大幅下降,且导致严重的膜污染. 温度对厌氧反应过程中有机物转化规律和微生物菌群结构均具有显著影响^[17,18]. 但是,目前有关温度对实际城市污水厌氧生物滤池去除效果、有机物的转化规律及微生物菌落结构的研究未见报道.

基于此本文以实际城市污水为研究对象,采用厌氧生物滤池中试装置,对厌氧生物滤池处理实际城市污水的启动方式和温度对系统运行效果的影响进行了分析,并进一步探究了温度对厌氧生化反应过程和菌群结构的影响.

1 材料与方法

1.1 中试反应装置

本研究采用下向流厌氧生物滤池,中试装置材质为不锈钢(图 1). 反应器有效容积为 240 L,长宽高分别为 0.5、0.4 和 2.6 m. 中试装置配有气体收集系统和反冲洗系统,其上部设置筛网进行预处理. 所用滤料为火山岩滤料,直径 4~6 mm,滤层装填高度 1.2 m. 运行期间未对温度进行调控,为污水的实际温度.

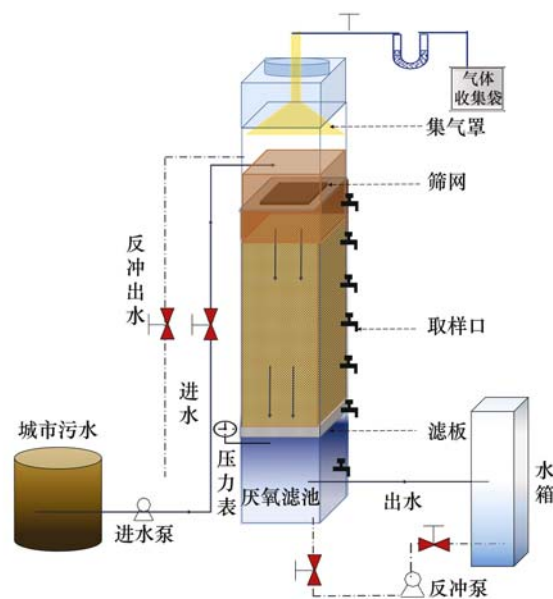


图 1 厌氧生物滤池中试装置示意

Fig. 1 Schematic pilot plant of anaerobic biofilter

1.2 实验用水与接种污泥

原污水取自北京市高碑店污水处理厂,进水中 TCOD、SCOD、 NH_4^+-N 、 NO_2^--N 和 NO_3^--N 的浓度分别为 115.4~344.1、77.56~147.5、31.52~51.52、0.00~1.14 和 0.00~2.27 $\text{mg}\cdot\text{L}^{-1}$.

接种污泥取自北京市清河地区管道底泥和某柠檬酸废水处理厂的厌氧颗粒污泥,两种污泥投加比例为 4:1,最终污泥浓度(MLSS)为 3.98 $\text{g}\cdot\text{L}^{-1}$.

1.3 实验设计

本研究分为启动和温度变化两个阶段. 启动阶段:先间歇运行 5 个周期,每个周期 48 h,而后连续运行挂膜 70 d, HRT 逐步降低(48 h→24 h→18 h). 温度变化阶段:系统 HRT 为 12 h,实际城市污水水温随时间分阶段梯度降温,第 70~98 d 平均温度 19℃,第 99~130 d 平均温度 14℃,第 131~168 d 平均温度 10℃,第 169~209 d 室外温度过低进行低温保护,第 210~245 d 反应器恢复运行,平均温度 19℃. 本实验过程中对关键节点,种泥、19℃(第 98 d)、14℃(第 130 d)和 10℃(第 168 d)的生物膜样品进行了高通量测序分析;对种泥、连续运行第 70 d 结束、19℃(第 98 d)、14℃(第 130 d)和 10℃(第 168 d)的生物膜样品进行了实时荧光定量 PCR 分析.

1.4 测定项目与方法

TCOD、SCOD、 NH_4^+-N 、 NO_2^--N 、 NO_3^--N 和 MLSS 按照国家环境保护局发布的标准方法测定^[19]. DO、pH 和 NTU 采用在线检测仪测定(德国,WTW 3630).

扫描电镜^[20]:首先用 2.5% 的戊二醛对滤料表

面生物膜进行固定,用磷酸缓冲液冲洗3次,之后依次用浓度为50%、70%、80%、90%和100%的乙醇进行脱水,每次10~15 min.然后分别用100%乙醇和乙酸异戊酯(1:1),纯乙酸异戊酯各置换一次,每次15 min.干燥后进行喷金,采用扫描式电子显微镜(日立S-3400N)对样品进行观察.

挥发性脂肪酸(volatile fatty acid, VFA)^[15]:采用气相色谱进行测定(Agilent 7890A),检测器和色谱柱分别为氢火焰离子化检测器(flame ionization detector, FID)和DB-WAXETR色谱柱(30 m × 1.0 μm × 0.53 mm).

溶解态甲烷采用上部空间法测定^[21]:采用气相色谱进行测定(Agilent 7890A),检测器和色谱柱分别为氢火焰离子化检测器(flame ionization detector, FID)和J&WHP-PLOT Q色谱柱(30 m × 40 μm × 0.53 mm).

1.5 微生物菌落结构分析方法

污泥和生物膜样品DNA提取后,进行实时荧光定量PCR与高通量测序分析.滤料上的生物膜通过振荡与滤料剥离,污泥或剥落的生物膜采用DNA快速提取试剂盒(MP Biomedicals, Solon, OH, USA)进行DNA提取.实时荧光定量PCR反应扩增引物及条件详见文献[22].高通量测序选用针对细菌16S基因的V3~V4区域,合成特异引物338F(5'-ACTCCTACGGGAGGCAGCA-3')和860R(5'-GGAC TACHVGGGTWTCTAAT-3')进行扩增,扩增目的片段长度468bp. PCR扩增采用TransStart Fastpfu DNA Polymerase和ABI GeneAmp® 9700型PCR仪进行.对PCR产物进行琼脂糖凝胶电泳检测,使用AxyPrepDNA凝胶回收试剂盒(AXYGEN公司)切胶回收PCR产物,Tris-HCl洗脱;根据电泳初步定量结果,将PCR产物用QuantiFluor™-ST蓝色荧光定量系统(Promega公司)进行检测定量.然后构建MiSeq文库进行MiSeq测序.测序完成后,对得到的PE reads进行序列数据拼接,同时对序列质量进行质控和过滤.利用Usearch软件优化序列,提取非重复序列,按照97%相似性对非重复序列(不含单序列)进行OTU聚类,划分OTU,并根据OTU的序列组成得到物种分类.使用97%相似度的OTU,应用Mothur软件分析相似水平下的Coverage、Chao、Shannon和Simpson等指数.

2 结果与讨论

2.1 中试厌氧生物滤池的启动

图2给出了启动阶段间歇运行过程中TCOD、SCOD浓度及去除率变化情况.从滤池上部投加种

泥后,进原污水间歇运行,第1个周期出水TCOD和SCOD去除率仅为10%.第2个周期TCOD去除率上升至43%,但SCOD去除率仍仅为12%.从第3个周期开始SCOD去除率上升至41%.TCOD的去除主要是由于生物滤池对原水中固体有机物的过滤作用.第3个周期后SCOD开始上升,该结果表明投加的厌氧微生物逐渐适应了城市污水低有机物浓度的环境条件.仅运行了2个周期,厌氧微生物活性就得到了恢复,这主要是由于本研究所用种泥大部分取自城市排水管道底泥,该污泥长期处于实际城市污水中,含有大量适宜处理城市污水的厌氧菌,这有利于厌氧生物滤池的快速启动.

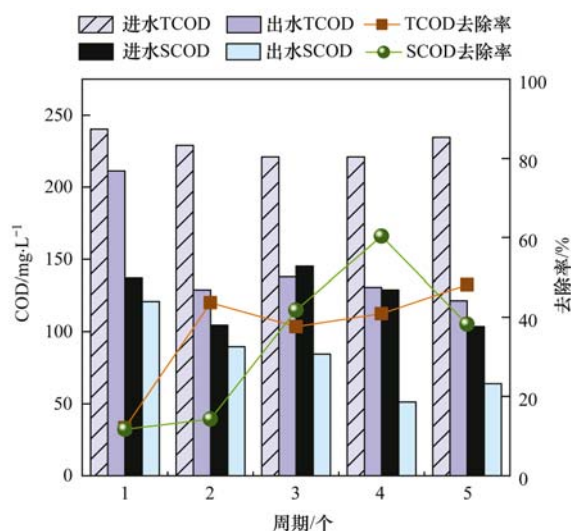
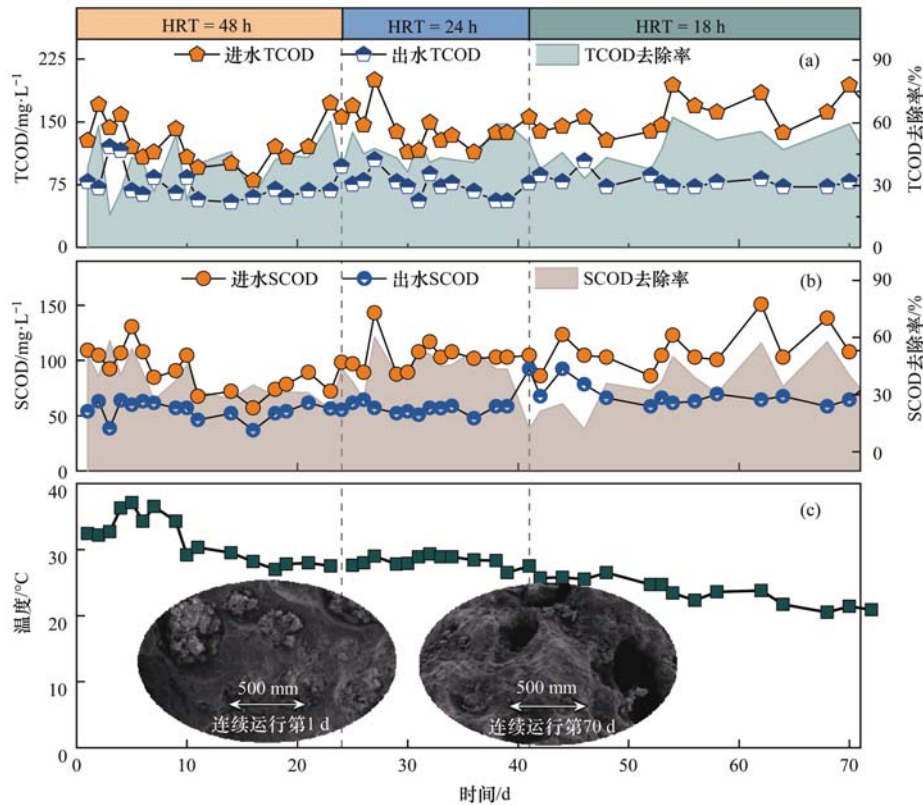


图2 启动阶段间歇运行过程中TCOD、SCOD浓度及去除率变化情况

Fig. 2 Variations in TCOD and SCOD concentrations, and removal rate of anaerobic biofilter under the intermittent process at start-up periods

图3(a)和3(b)给出了启动阶段连续运行过程中TCOD、SCOD浓度和去除率的变化情况.运行前4 d, TCOD和SCOD出水不稳定,第2~4 d,滤池出水TCOD升高,这可能是滤料表面达到吸附平衡后,在水力剪切作用下,吸附不牢固的微生物或悬浮物质被冲刷出系统^[23,24].第5 d,出水TCOD和SCOD分别降至78 mg·L⁻¹和53 mg·L⁻¹.此后,出水TCOD和SCOD趋于稳定.第24~41 d, HRT降为24 h,该过程中出水TCOD和SCOD基本稳定在75 mg·L⁻¹和56 mg·L⁻¹.进一步降低HRT为18 h,出水TCOD和SCOD上升至103 mg·L⁻¹和92 mg·L⁻¹,运行8 d后,逐渐恢复至72 mg·L⁻¹和63 mg·L⁻¹,此阶段后期虽然温度降至24.7℃,但出水TCOD和SCOD仍稳定在76 mg·L⁻¹和65 mg·L⁻¹.图3(c)给出了启动阶段连续运行过程中温度、第1 d和第70 d滤料表面扫描电镜的测试结果.间歇进水结束,连续运行



(a) TCOD 浓度与去除率; (b) SCOD 浓度与去除率; (c) 温度变化与滤料表面扫描电镜结果

图3 启动阶段连续运行过程中厌氧生物滤运行情况

Fig. 3 Performance of anaerobic biofilter under continuous process at the start-up periods

第1 d, 滤料孔洞里生长聚集了大量微生物, 但孔洞以外的滤料表面较光滑. 连续运行70 d后, 滤料表面变得粗糙不平, 表面有大量微生物聚集, 该结果说明生物滤池已经形成了厌氧生物膜. 稳定的出水SCOD、TCOD和扫描电镜测试结果均说明厌氧滤池已启动成功.

采用先间歇后连续运行的方式, 有利于厌氧生物滤池的快速启动, 间歇运行有利于厌氧菌活性恢复, 连续运行并逐渐降低HRT可逐渐增加水力剪切作用, 从而促进生物膜的快速形成. 启动过程中虽然实际污水进水COD波动较大, 但出水SCOD仍稳定维持在60 mg·L⁻¹, 说明厌氧生物滤池工艺具有较强的抗冲击负荷能力.

2.2 温度对厌氧生物滤池运行的影响

2.2.1 系统运行情况

图4给出了温度变化阶段厌氧生物滤池内TCOD、SCOD和去除率变化情况. 从第70 d进水温度开始下降, 73~98 d, 温度较稳定平均为19°C, 出水TCOD和SCOD浓度较稳定, 分别维持在90 mg·L⁻¹和75 mg·L⁻¹. 第98 d后, 水温缓慢下降, 水温约为14°C; 该阶段运行前8 d, 出水TCOD和SCOD分别上升至110 mg·L⁻¹和85 mg·L⁻¹; 此后, 出水TCOD和SCOD恢复稳定, 浓度分别为90

mg·L⁻¹和69 mg·L⁻¹. 第130~169 d, 水温在10°C左右波动, 最低可达8.7°C; 该阶段出水SCOD仍维持在68 mg·L⁻¹, 但出水TCOD浓度明显升高, 平均浓度为120 mg·L⁻¹. 本实验结果表明: 温度高于14°C时, 厌氧生物滤池系统对SCOD和TCOD的去除均较为稳定; 当温度在10°C左右时, 系统出水SCOD仍较低, 但出水TCOD明显升高, TCOD去除率由55%降低至35%. Bandara等^[25]采用UASB处理城市污水的研究时发现, 当温度低于10°C时, 其TCOD去除率低于10%. 实际城市污水水温逐渐下降, 厌氧微生物可逐渐适应这种温度变化过程, 因此, 即使温度在10°C左右, 溶解性有机物去除能力仍较高. 但是冬季温度较低时, 悬浮固体有机物占TCOD的比例也有所上升^[26, 27]; 进水COD组成的变化和较低的温度, 使得水解速率降低^[28], 因此, 当温度在10°C左右, TCOD去除率显著降低.

本装置放置在室外, 当系统温度低于10°C时, 为保护整个系统而采取放空闲置的方式, 系统进入低温保护阶段, 系统平均水温约5°C, 40 d后气温升高, 恢复系统运行, 第209~245 d, 平均水温为19°C, 运行4 d后, TCOD和SCOD去除率基本恢复, 出水TCOD和SCOD分别维持在100 mg·L⁻¹和73 mg·L⁻¹. 经过较长时间的低温运行和低温闲置, 厌

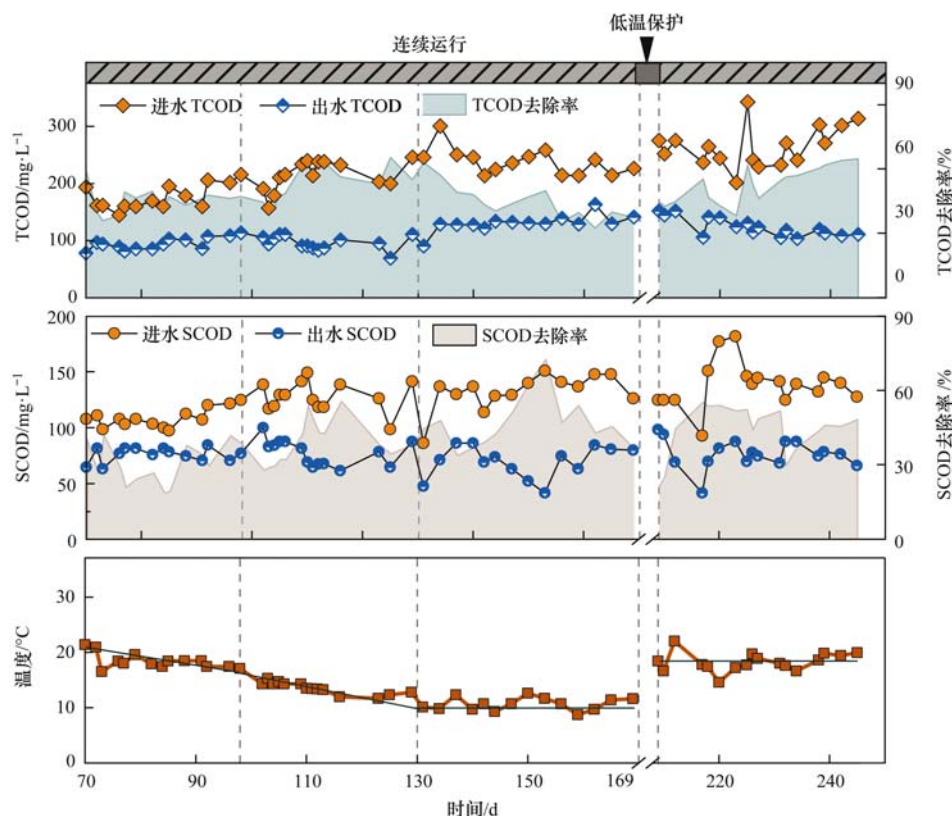


图4 温度变化阶段厌氧生物滤池运行情况

Fig. 4 Performance of anaerobic biofilter at temperature variation periods

氧生物滤池的处理效果仍能快速恢复,该结果说明厌氧生物滤池具有较强的抗冲击能力和低温运行能力。

厌氧生物滤池运行 285 d,滤池底部压力与静水压力基本相同,说明滤层未发生堵塞,无需对厌氧生物滤池进行反冲洗。该结果进一步证实了由于厌氧生物滤池内微生物生长缓慢,厌氧生物滤池基本不需要进行反冲洗。与目前广泛采用的好氧硝化和反硝化滤池相比,厌氧生物滤池不存在滤池堵塞与频繁反冲洗问题,可充分发挥生物滤池抗冲击能力强,生化反应与过滤于一体的优势。

2.2.2 有机物的降解与转化过程

图 5 给出了温度变化阶段厌氧滤池沿滤层高度 TCOD、SCOD 和 VFA 浓度的典型变化。水温为 19℃ (I) 和 14℃ 条件下,有机物降解趋势基本相同,TCOD 逐渐降低,而 SCOD 和 VFA 先上升后下降;厌氧反应产生的 VFA 以乙酸为主,但出水中仅含有乙酸,且浓度低于 5 mg·L⁻¹。本实验结果表明:当温度高于 14℃ 时,进水混合和滤层顶部发生了水解酸化反应,将非溶解性有机物转化为乙酸等溶解性有机物,随后在滤层中发生产甲烷反应。同时,温度在 14℃ 以上运行时,出水 VFA 浓度均较低,说明系统内水解酸化菌和产甲烷菌代谢较为平衡^[29]。

当温度为 10℃ 时,TCOD 和 SCOD 在进水混合

和滤层底部,基本无变化;而系统出水 TCOD 升高(图 4)。该结果进一步证实了水解反应更易受到低温条件的影响。同时,10℃ 时反应过程中 VFA 浓度均高于 19℃ (I) 和 14℃,出水 VFA 浓度约 12 mg·L⁻¹。该结果说明当温度降至 10℃ 时,系统内水解反应、VFA 利用速率和产甲烷活性可能均有所降低。当温度恢复到 19℃ (II) 后,出水 TCOD 逐渐下降(图 4),出水 VFA 浓度恢复至 5 mg·L⁻¹,说明温度升高后,系统水解和产甲烷活性均得以恢复。

2.2.3 产甲烷情况

图 6 给出了温度变化阶段厌氧滤池内溶解态甲烷产率和 TCOD 浓度变化情况。由于本研究所用滤池为下向流生物滤池,且城市污水 TCOD 浓度较低,不同温度条件下,厌氧生物滤池产生的甲烷主要为溶解态甲烷。在温度为 14℃ 以上运行时,甲烷产率(以 CH₄/TCOD 计)稳定在 0.34 g·g⁻¹;当温度降至 10℃ 时,系统甲烷产率有所下降,降为 0.32 g·g⁻¹。该结果表明 14℃ 以上时,温度变化对系统产甲烷过程的影响较小;但当温度较低时导致系统产甲烷能力降低。

2.3 厌氧生物滤池菌群结构变化

2.3.1 菌群结构分析

表 1 给出了种泥、19℃、14℃ 和 10℃ 下厌氧生物膜样品微生物群落多样性指数。19℃ 时,Shannon

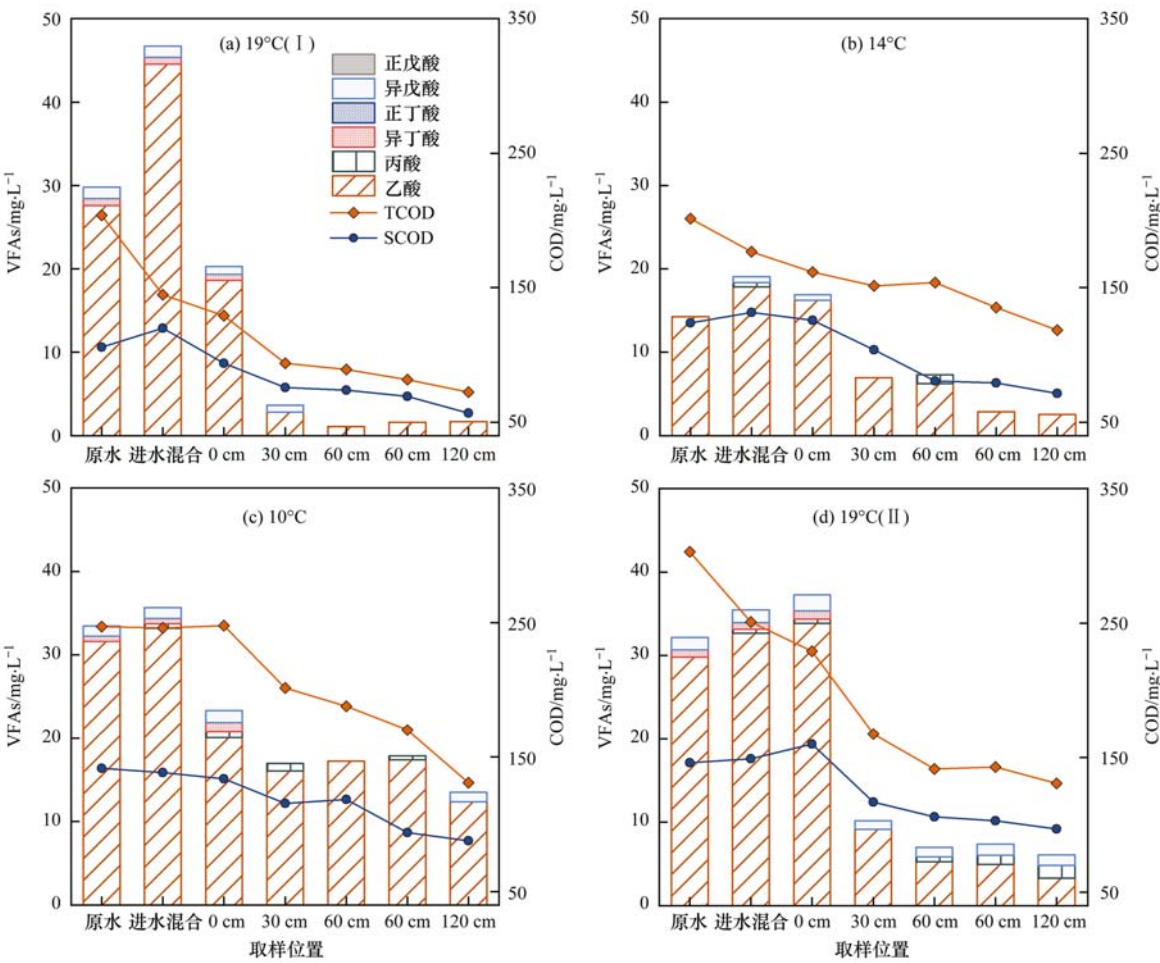


图 5 温度变化阶段厌氧滤池内 TCOD、SCOD 和 VFA 浓度的典型变化

Fig. 5 Typical variations diagram in TCOD, SCOD, and VFA concentration at temperature variation periods

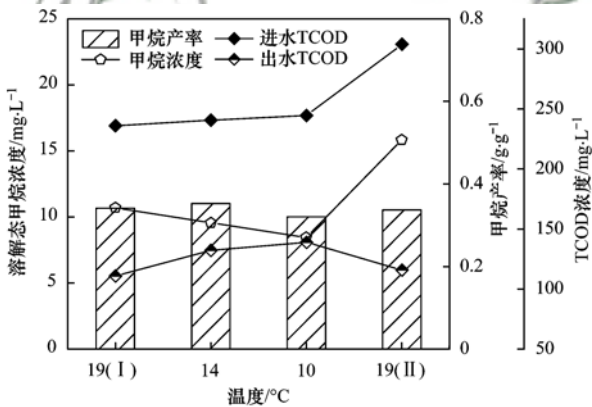


图 6 温度变化阶段厌氧滤池溶解态甲烷浓度、甲烷产率和 TCOD 浓度变化情况

Fig. 6 Variations in dissolved methane concentration, methane production, and TCOD concentration in anaerobic biofilter at temperature variation periods

指数和 Chao 值最高,而 Simpson 指数最小.该结果说明 19℃时系统内菌群丰富度和多样性最高,而当温度逐渐下降至 10℃时菌群的丰富度和多样性均降低.

图 7 给出了厌氧滤池种泥、19℃、14℃和 10℃下生物膜样品在细菌门水平上菌群组成情况,系统内的优势菌为厚壁菌门 (Firmicutes)、变形菌门 (Proteobacteria)、放线菌门 (Actinobacteria) 和绿弯菌门 (Chloroflexi),这些都是厌氧系统常见的微生物.当温度由 19℃降至 10℃时,厚壁菌门 (Firmicutes) 相对丰度由 40.67% 上升至 60.12%,而绿弯菌门 (Chloroflexi) 相对丰度由 12.09% 降至 4.65%,变形菌门 (Proteobacteria) 相对丰度由 16.43% 降至 14.43%.

表 1 不同阶段生物膜样品微生物群落多样性指数

Table 1 Microbial community diversity index in different periods

项目	Shannon 指数	Simpson 指数	Chao 指数	Coverage 指数
种泥	4.147 126	0.063 632	1 429.441 489	0.996 337
T = 19℃	4.969 703	0.039 743	2 095.735 974	0.992 752
T = 14℃	4.851 968	0.071 276	2 026.260 8	0.990 63
T = 10℃	4.223 66	0.107 524	1 888.060 837	0.992 561

厚壁菌门(Firmicutes)是水解阶段的重要菌群,主要负责有机物的分解,其对不利条件的耐受性较高^[30],所以在 10℃ 时,厚壁菌门(Firmicutes)相对丰度上升,这可能是 10℃ 时出水 SCOD 仍较好的原因.绿弯菌门(Chloroflexi)在好氧和厌氧环境下,具有降解多种大分子物质的功能;变形菌门(Proteobacteria)是厌氧消化过程中重要的微生物菌群,其具有诱导细胞裂解并释放胞内物质的功能^[31].绿弯菌门(Chloroflexi)和变形菌门(Proteobacteria) 10℃ 时相对丰度降低,使系统对悬浮固体等大分子有机物降解能力下降,导致了系统出水 TCOD 的升高.

图 8 给出了厌氧滤池种泥、19℃、14℃ 和 10℃ 下生物膜样品在细菌科水平上菌群组成情况.红环菌科(Rhodocyclaceae)和瘤胃菌科(Ruminococcaceae)均是参与水解过程的关键菌群^[32],红环菌科(Rhodocyclaceae)和瘤胃菌科(Ruminococcaceae)相对丰度在 19℃ 和 14℃ 时升高,在 10℃ 时下降.该结果进一步证实了 10℃ 的低温条件易导致水解菌群减少,水解反应速率降低,是系统出水 TCOD 浓度升高的主要原因.

消化链球菌科(Peptostreptococcaceae)和梭菌科(Clostridiaceae)是系统内优势菌群.当温度由 19℃ 降至 10℃ 时,消化链球菌科(Peptostreptococcaceae)相对占比由 7.9% 上升至 32.79%;而梭菌科(Clostridiaceae)由 23.10% 降至 10.05%.消化链球菌科(Peptostreptococcaceae)主要以蛋白质和碳水化

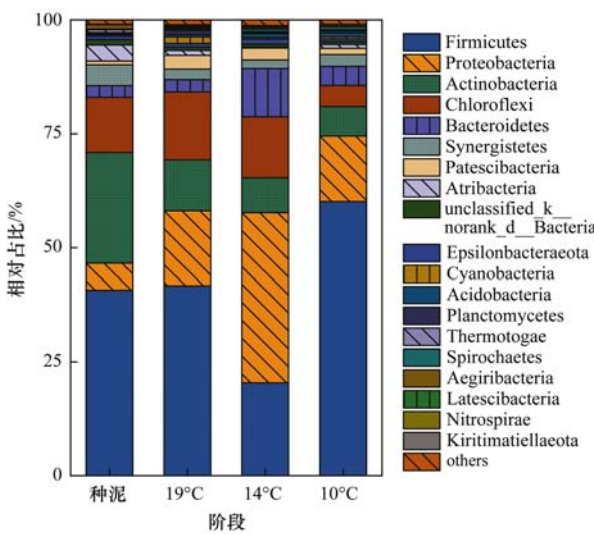


图 7 不同阶段样品在细菌门水平上菌群组成情况

Fig. 7 Relative abundance of different phylum of bacteria in different periods

合物等为底物反应生成乙酸和丁酸等,为乙酸型产甲烷菌提供底物;而梭菌科(Clostridiaceae)能利用纤维素和木质素等产生氢气,为氢营养型产甲烷菌提供底物^[33].低温条件使产酸菌消化链球菌科(Peptostreptococcaceae)相对丰度升高,这可能是系统 10℃ 反应过程中 VFA 浓度较高的主要原因.

2.3.2 功能菌群丰度分析

为进一步确定低温对产甲烷菌的影响,本研究对不同温度条件下产甲烷菌菌群丰度进行了分析(图 9).本研究共对甲烷八叠球菌目(Methanosarcinales)、甲烷杆菌目(Methanobacteriales)和甲烷微菌目

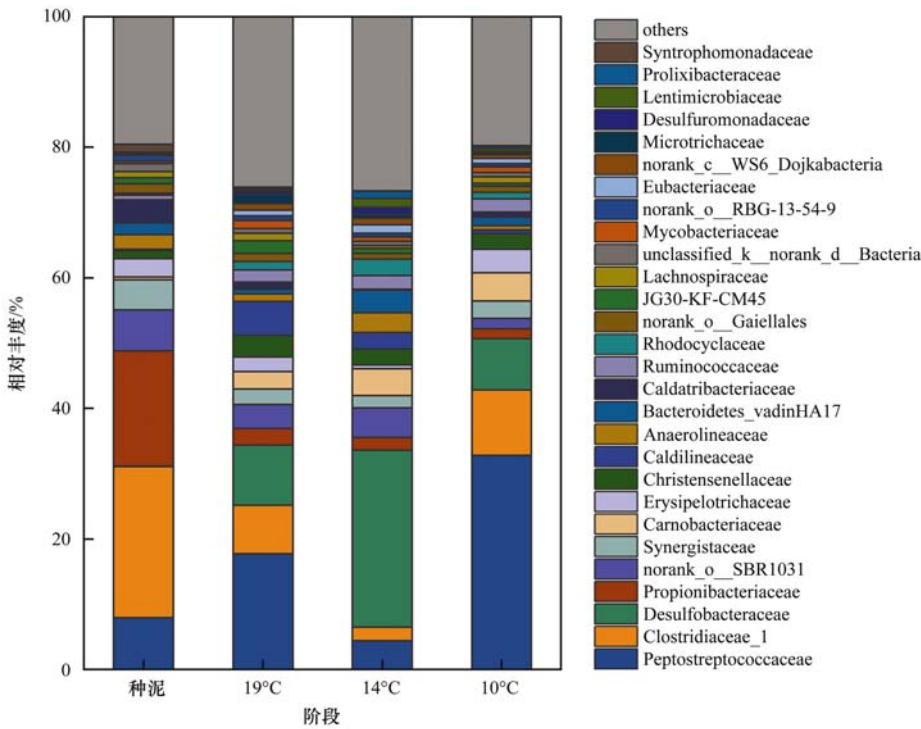


图 8 不同阶段样品在细菌科水平上菌群组成情况

Fig. 8 Relative abundance of different family of bacteria in different periods

(Methanomicrobiales)这3种产甲烷菌进行了定量分析.其中甲烷八叠球菌目(Methanosarcinales)为乙酸型产甲烷菌,甲烷杆菌目(Methanobacteriales)和甲烷微菌目(Methanomicrobiales)为氢营养型产甲烷菌.

当温度逐渐降低至14℃时,系统内氢营养型产甲烷菌,甲烷杆菌目(Methanobacteriales)菌群丰度由 1.33×10^{11} copies·g⁻¹下降至 4.00×10^{10} copies·g⁻¹,下降了3.325倍;甲烷微菌目(Methanomicrobiales)菌群丰度略有增加.这可能是低温条件下氢营养型水解酸化菌减少,导致氢产量降低,使得氢营养型产甲烷菌反应受到底物限制^[34, 35].乙酸型产甲烷菌甲烷八叠球菌目(Methanosarcinales)菌群为系统中的优势菌属,菌群丰度由 1.35×10^{10} copies·g⁻¹升高至 1.52×10^{11} copies·g⁻¹.随温度的降低,乙酸型产甲烷菌群丰度逐渐升高,该结果说明温度降低使得产甲烷菌群结构发生了变化.

当温度进一步降低至10℃时,甲烷八叠球菌目(Methanosarcinales)、甲烷杆菌目(Methanobacteriales)和甲烷微菌目(Methanomicrobiales)菌群丰度均降低,但乙酸型产甲烷菌甲烷八叠球菌目(Methanosarcinales)菌群丰度由 1.52×10^{11} copies·g⁻¹降至 2.64×10^{10} copies·g⁻¹,仍为系统优势菌属.由于低温条件(10℃),产甲烷菌丰度降低,产甲烷菌菌群结构发生变化,使得温度为10℃时,系统反应过程中VFA升高(图5),甲烷产率有所下降(图6).

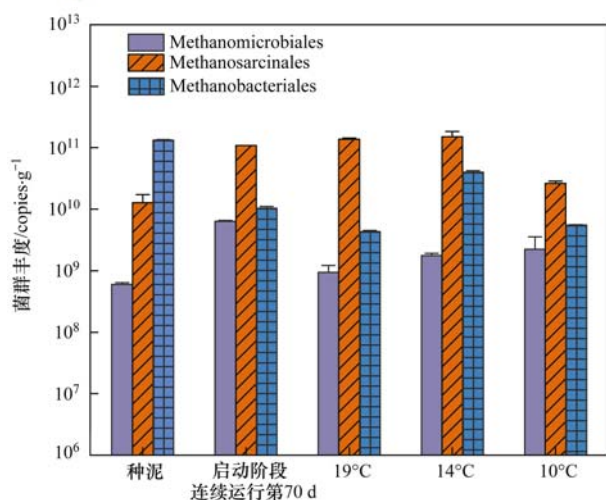


图9 不同阶段样品产甲烷功能菌菌群丰度变化情况

Fig. 9 Variations in methanogens abundance in anaerobic biofilter in different periods

3 结论

(1)中试厌氧生物滤池处理实际城市污水,采用间歇运行和连续运行相结合的挂膜方式,可实现

工艺的快速启动.启动成功后,TCOD和SCOD去除率最高可达60%和62%,出水SCOD浓度稳定在60 mg·L⁻¹.

(2)城市污水厌氧生物滤池不但具有启动快和抗冲击能力强等优点,而且可长时间(9个月)稳定运行,不需反冲洗,避免了生物滤池频繁反冲洗的问题.

(3)14℃以上厌氧生物滤池运行较稳定,水解酸化菌和产甲烷菌代谢趋于平衡,出水SCOD和TCOD可稳定在69 mg·L⁻¹和90 mg·L⁻¹.10℃的低温条件易导致水解菌群相对丰度下降,消化链球菌科(Peptostreptococcaceae)产酸菌相对丰度增加,产甲烷菌群数量略有降低,因而导致反应过程中TCOD去除效果下降,VFA浓度较高,产甲烷能力略有降低,但出水SCOD较为稳定.

(4)厌氧生物滤池生物膜菌群结构复杂,菌群丰富度和多样性随温度的降低而下降.同时,启动和温度降低过程中,产甲烷菌群结构发生变化,乙酸型产甲烷菌群丰度逐渐升高,成为产甲烷优势菌群.

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