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# ABR 除碳-亚硝化耦合厌氧氨氧化处理城市污水

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**摘要:** 为推进厌氧氨氧化技术应用于城市污水处理, 耦合亚硝化系统和厌氧氨氧化系统, 并在其前端添加 ABR 除碳系统, 构建 ABR 除碳-亚硝化耦合厌氧氨氧化工艺进行城市污水脱氮除碳, 采用 MiSeq 高通量测序技术分析污泥中微生物菌群结构的变化情况. 结果表明, ABR 除碳系统出水 COD 平均浓度  $120 \text{ mg} \cdot \text{L}^{-1}$ , 不会对后续亚硝化系统和厌氧氨氧化系统产生不利影响, 控制亚硝化系统出水和 ABR 除碳出水比例为 2:1 作为厌氧氨氧化系统进水, 满足 ANAMMOX 所需  $\text{NO}_2^- \text{-N}$  和  $\text{NH}_4^+ \text{-N}$  基质比 1:1 左右的要求. 一体式反应器总氮去除率在 86% ~ 92%, 出水 COD 浓度在  $20 \sim 40 \text{ mg} \cdot \text{L}^{-1}$ . 同时, 实验后亚硝化系统中与反硝化作用密切相关的  $\gamma$ -Proteobacteria 纲有所增加, 厌氧氨氧化系统中具有较高微生物生长速率和增强脱氮速率功能的 Sphingobacteria 纲显著增加, ABR 除碳-亚硝化耦合厌氧氨氧化工艺能够有效用于处理城市污水脱氮除碳.

**关键词:** 厌氧氨氧化; 亚硝化; 一体式反应器; 微生物菌群结构

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## ABR Decarbonization-Nitrosation Coupled with ANAMMOX to Treat Municipal Wastewater

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**Abstract:** In order to promote the application of anaerobic ammonium oxidation (ANAMMOX) to treat municipal wastewater, nitrosation was coupled with ANAMMOX and an ABR decarbonization system at the front of it; then used to build a system in which ABR decarbonization-nitrosation coupled with ANAMMOX was used to treat municipal wastewater. The high throughput sequencing technology of MiSeq was employed to analyze the structure of the microbial community in the sludge. Results showed that the average effluent COD concentration of the carbon removal system was  $120 \text{ mg} \cdot \text{L}^{-1}$  and that the subsequent nitrosation system and ANAMMOX system would not be adversely affected by the effluent COD. Controlled by matching the nitrosation effluent with that from the ABR carbon removal system 2:1, the ANAMMOX influent, kept the ratio of the  $\text{NO}_2^- \text{-N}$  and  $\text{NH}_4^+ \text{-N}$  matrix to ANAMMOX at about 1:1. The total nitrogen removal rate of the integrated reactor was 86% - 92% and the COD of the effluent was  $20 \sim 40 \text{ mg} \cdot \text{L}^{-1}$ . After the experiment, the number of bacteria in class  $\gamma$ -Proteobacteria in the nitrosation system, which are closely related to denitrification, increased. Members of class Sphingobacteria, which have the function of enhancing the growth rate of microorganisms and enhancing the rate of denitrification, were significantly increased in the ANAMMOX system. The nitrogen and carbon in the municipal wastewater could be stably and efficiently removed by the ABR Decarbonization-Nitrosation coupled with ANAMMOX process.

**Key words:** anaerobic ammonium oxidation (ANAMMOX); nitrosation; integrated reactor; structure of microbial community

随着水体中氮素污染日益严重, 已经影响到了人类健康, 我国控制 N、P 的排放也越来越严格. 新的排放标准对脱氮工艺提出了更高的要求, 传统脱氮工艺已无法满足可持续发展的要求, 经济高效的新型脱氮工艺亟需开发. 厌氧氨氧化<sup>[1]</sup> (anaerobic ammonium oxidation, ANAMMOX) 反应是指在厌氧或缺氧条件下, 厌氧氨氧化微生物以  $\text{NO}_2^- \text{-N}$  为受体, 氧化  $\text{NH}_4^+ \text{-N}$  为氮气的过程, 凭借工艺流程简短、无需外加有机碳源、曝气能耗低、污泥产量低等优势, 成为污水生物脱氮领域的研究热点<sup>[2~5]</sup>. 近年来, 国内外研究开发了多种以厌氧氨氧化为主体的污水处理工艺, 其中最为广泛的为亚硝化-厌氧氨氧化工艺 (Sharon-ANAMMOX)<sup>[4~6]</sup>. 该工艺在亚硝化阶段将

原废水中 50% ~ 60% 的  $\text{NH}_4^+ \text{-N}$  转化为  $\text{NO}_2^- \text{-N}$ , 在 ANAMMOX 阶段, ANAMMOX 菌将剩余的  $\text{NH}_4^+ \text{-N}$  与在亚硝化生成的  $\text{NO}_2^- \text{-N}$  进行厌氧氨氧化反应生成氮气<sup>[7~9]</sup>.

目前亚硝化-厌氧氨氧化工艺已在高氨氮废水领域得到了广泛应用, 而在低氨氮废水处理领域的应用尚不成熟. 本课题组基于前期的研究成

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果<sup>[10,11]</sup>,构建连续流完全混合反应器(CSTR)亚硝化-膜生物反应器(MBR)厌氧氨氧化系统,且为减少有机碳源对亚硝化及厌氧氨氧化的影响,在CSTR-MBR前端设置ABR除碳系统,将三者耦合成一体化ABR除碳-CSTR亚硝化-MBR厌氧氨氧化工艺处理生活污水,同时采用MiSeq高通量测序技术对系统内微生物进行检测,从分子生物学角度分析菌群结构变化,以期ABR除碳-亚硝化-厌氧氨氧化工艺处理城市生活污水提供宏观和微观依据。

## 1 材料与方法

### 1.1 实验装置

本实验装置由有机玻璃制成,如图1,总有效体积16.24 L,反应器长63 cm,宽8 cm,有效高度30 cm,由ABR除碳系统、CSTR亚硝化和MBR厌氧氨氧化系统组成。ABR系统每隔室升流区和降流区隔间宽度比为4:1,折流板导向角为45°,有效容积为8.8 L。亚硝化系统为连续流完全混合式反应器,分为曝气池和沉淀池两部分组成,有效容积分别为2.64 L和0.96 L。厌氧氨氧化反应器中设置帘式中空纤维微滤膜组件,膜孔径0.1 μm,膜面积为0.2 m<sup>2</sup>,有效容积为3.84 L。MBR厌氧氨氧化进水由ABR除碳系统出水和亚硝化出水两部分组成,以此保证厌氧氨氧化进水NH<sub>4</sub><sup>+</sup>-N:NO<sub>2</sub><sup>-</sup>-N浓度在1:1左右。一体式反应器通过蠕动泵连续进水,由蠕动泵经中空纤维微滤膜间歇抽吸出水,抽吸周期为10 min(8 min抽吸和2 min反冲洗)。整个反应器始终置于恒温水浴箱中,温度控制在(30 ± 1) °C。

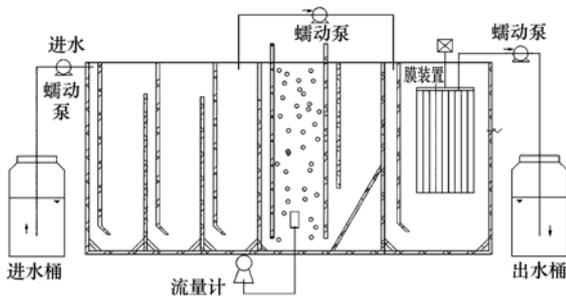


图1 实验装置示意

Fig. 1 Experimental apparatus

### 1.2 接种污泥和实验进水

ABR除碳污泥取自苏州某生活污水处理厂缺氧池污泥,ABR反应器各隔室接种污泥约占各隔室容积的2/3,污泥浓度(MLSS)为7.9 g·L<sup>-1</sup>。亚硝化污泥和厌氧氨氧化污泥均来自于实验室的亚硝化反应器和厌氧氨氧化反应器,MLSS分别为4.5 g·L<sup>-1</sup>和6.9 g·L<sup>-1</sup>。

采用人工配水模拟城市污水,以(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>为

氮源(NH<sub>4</sub><sup>+</sup>-N浓度为50 mg·L<sup>-1</sup>左右),以乙酸钠为碳源(COD浓度为300~400 mg·L<sup>-1</sup>),加碳酸氢钠以调节pH至7.5左右。另外还包括生物所需的其他营养元素氯化钙(10 mg·L<sup>-1</sup>)、硫酸镁(10 mg·L<sup>-1</sup>)、磷酸氢二钾(4 mg·L<sup>-1</sup>)及微量元素。微量元素分为微量元素I和微量元素II,微量元素按照1 mL·L<sup>-1</sup>添加。微量元素I组分(g·L<sup>-1</sup>): EDTA 5, FeSO<sub>4</sub> 5;微量元素II组分(g·L<sup>-1</sup>): EDTA 15, ZnSO<sub>4</sub>·7H<sub>2</sub>O 0.43, CoCl<sub>2</sub>·6H<sub>2</sub>O 0.24, MnCl<sub>2</sub>·4H<sub>2</sub>O 0.99, CuSO<sub>4</sub>·5H<sub>2</sub>O 0.25, NaMoO<sub>4</sub>·2H<sub>2</sub>O 0.22, NiCl<sub>2</sub>·6H<sub>2</sub>O 0.19, NaSeO<sub>4</sub>·10H<sub>2</sub>O 0.21, H<sub>3</sub>BO<sub>4</sub> 0.014。

### 1.3 分析方法

本实验过程中每隔1 d取水样测定,测定项目主要包括: NH<sub>4</sub><sup>+</sup>-N; 纳氏试剂分光光度法; NO<sub>2</sub><sup>-</sup>-N; N-(1-萘基)-乙二胺分光光度法; NO<sub>3</sub><sup>-</sup>-N; 紫外分光光度法; MLSS、MLVSS: 标准重量法; SVI: 30 min 沉降法; pH: pHs-9V 数显酸度计; 溶解氧: YSI550A 溶氧仪。

### 1.4 微生物高通量测序分析

分别将实验前后的CANON系统中污泥采集送样,采用FastPrep DNA提取试剂盒(QBIOGENE, USA)DNA,完成基因组DNA抽提后,利用1%琼脂糖凝胶电泳检测抽提的基因组DNA。用16S rRNA基因引物338F(ACTCCTACGGGAGGCAGCAG)和806R(GGACTACHVGGGTWTCTAAT)对细菌16S rRNA基因进行PCR扩增,PCR仪采用ABI GeneAmp® 9700型,采用TransGen AP221-02; TransStart Fastpfu DNA Polymerase, 20 μL反应体系。反应程序为95°C预变性3 min,95°C变性30 s,55°C退火30 s,72°C延伸45 s,27个循环后,72°C延伸10 min,每个样品重复3次。

使用AxyPrepDNA凝胶回收试剂盒(AXYGEN公司)切胶回收PCR产物,委托上海美吉生物医药科技有限公司完成对PCR扩增产物的高通量测序,微生物多样性分析于上海美吉医药生物科技有限公司所提供的I-Sanger生信分析云平台上完成。

## 2 结果与讨论

### 2.1 亚硝化系统

因为厌氧氨氧化反应的基质配比NH<sub>4</sub><sup>+</sup>-N:NO<sub>2</sub><sup>-</sup>-N浓度为1:1左右,所以亚硝化和厌氧氨氧化的联合工艺的关键在于如何实现稳定的部分亚硝化<sup>[12]</sup>,而实现长期稳定的部分亚硝化十分困难。本实验废水先经ABR除碳系统除碳后,一部分ABR除碳出水进入亚硝化进行完全亚硝化,另一部分

ABR 出水直接进入厌氧氨氧化系统中与亚硝化出水合并作为厌氧氨氧化进水,工艺路线如图 2. 本工艺路线同样可以保证厌氧氨氧化的进水中  $\text{NH}_4^+ - \text{N}$  和  $\text{NO}_2^- - \text{N}$  浓度比为 1:1, 而控制完全亚硝化比部分亚硝化要容易得多.

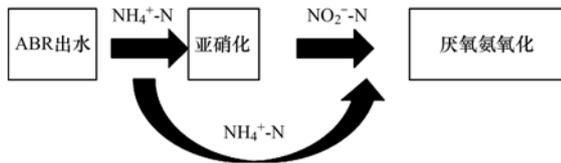


图 2 一体式亚硝化-厌氧氨氧化工艺路线

Fig. 2 Integrated nitrosation-ANAMMOX process route

在 ABR 除碳-亚硝化耦合厌氧氨氧化一体式工艺启动过程中,人工模拟城市污水,控制一体式反应器进水 COD 浓度  $300 \sim 400 \text{ mg} \cdot \text{L}^{-1}$ 、 $\text{NH}_4^+ - \text{N}$  浓度  $50 \text{ mg} \cdot \text{L}^{-1}$ 、pH 值 7.5 左右,一体式反应器 HRT 18 h. 此时 ABR 除碳系统出水 COD 浓度为  $120 \text{ mg} \cdot \text{L}^{-1}$ ,不会对后续亚硝化系统产生不利影响<sup>[13, 14]</sup>. 如图 3,控制亚硝化系统 HRT 为 3 h、DO 浓度为  $0.8 \sim 1.2 \text{ mg} \cdot \text{L}^{-1}$ ,亚硝化系统出水  $\text{NH}_4^+ - \text{N}$  浓度在前 5 d 后迅速降低至  $10 \text{ mg} \cdot \text{L}^{-1}$  以下,这与李田等<sup>[15]</sup>接种储存亚硝化污泥实验结果一致,出水  $\text{NO}_2^- - \text{N}$  逐步由  $20 \text{ mg} \cdot \text{L}^{-1}$  以下提升至  $35 \text{ mg} \cdot \text{L}^{-1}$  左右,出水  $\text{NO}_3^- - \text{N}$  浓度始终在  $6 \text{ mg} \cdot \text{L}^{-1}$  以下,出水 COD 浓度在  $40 \text{ mg} \cdot \text{L}^{-1}$  左右. 在接下来的 70 d 的一体式反应器启动过程中,亚硝化系统出水  $\text{NH}_4^+ - \text{N}$  浓度维持在  $6 \sim 10 \text{ mg} \cdot \text{L}^{-1}$ ,氨氮去除率在  $80\% \sim 90\%$ ,氨氮去除率并未进一步提高,是因为  $\text{NH}_4^+ - \text{N}$  出水浓度过低,会降低亚硝化系统中游离氨 (free ammonia, FA) 浓度. 有研究发现<sup>[16, 17]</sup>, FA 对氨氧化细菌 (ammonia oxidizing bacteria, AOB) 和亚硝酸盐氧化菌 (nitrite oxidizing bacteria, NOB) 产生抑制的浓度分别为  $10 \sim 150 \text{ mg} \cdot \text{L}^{-1}$  和  $0.1 \sim 1.0 \text{ mg} \cdot \text{L}^{-1}$ ,本实验亚硝化系统出水  $\text{NH}_4^+ - \text{N}$  浓度维持在  $6 \sim 10 \text{ mg} \cdot \text{L}^{-1}$ ,FA 浓度控制在  $2 \sim 10 \text{ mg} \cdot \text{L}^{-1}$ ,这也是本实验亚硝化系统出水  $\text{NO}_3^- - \text{N}$  较低的原因之一,亚硝累积率 (NAR) 在  $85\% \sim 93\%$ .

值得一提的是,在亚硝化系统的整个启动过程中,始终有  $10\% \sim 15\%$  的氮损存在,这是因为亚硝化反应器存在局部死区,造成局部厌氧环境,且亚硝化系统中同时有氨氮和亚硝态氮的存在,为厌氧氨氧化菌的生存提供了条件,发生了厌氧氨氧化反应<sup>[18]</sup>,故而出现氮损的现象. 在启动的前 5 d,甚至出现了出水总氮大于进水总氮的现象,这是由于部分接种的亚硝化污泥,不能适应所在环境的改变而发生细胞自溶,释放出大量的  $\text{NH}_4^+ - \text{N}$ .

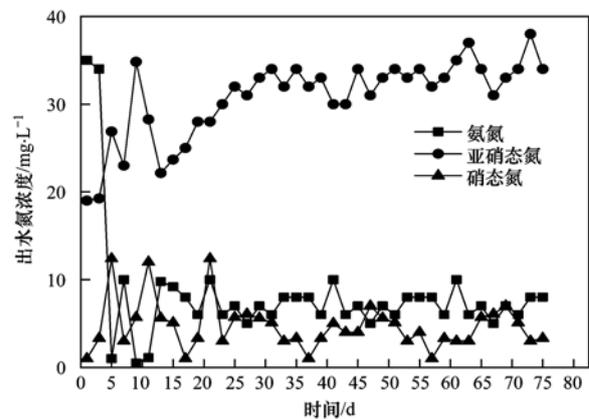
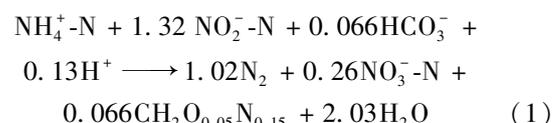


图 3 亚硝化出水氮浓度变化

Fig. 3 Change of effluent nitrogen concentration during nitrosation

## 2.2 厌氧氨氧化系统

厌氧氨氧化系统的进水由亚硝化系统出水和 ABR 除碳系统出水两部分组成,在一体式反应器启动的前 37 d 中,控制亚硝化系统出水和 ABR 除碳系统出水比例为 (1.5:1)、厌氧氨氧化系统 HRT 4.5 h,如图 4,此时厌氧氨氧化系统出水即一体式 ABR 除碳-亚硝化-厌氧氨氧化反应器出水  $\text{NH}_4^+ - \text{N}$  呈现先下降后上升的变化,出水  $\text{NO}_2^- - \text{N}$  一直处于较低水平 ( $1 \sim 3 \text{ mg} \cdot \text{L}^{-1}$ ). 这是因为本实验厌氧氨氧化系统中接种的是培养成熟的厌氧氨氧化污泥,污泥活性良好,故接种后一体式反应器出现出水  $\text{NH}_4^+ - \text{N}$  浓度迅速下降的现象;而 ABR 除碳系统出水中  $\text{NH}_4^+ - \text{N}$  浓度为  $50 \text{ mg} \cdot \text{L}^{-1}$ , $\text{NO}_2^- - \text{N}$  浓度为  $0 \text{ mg} \cdot \text{L}^{-1}$ ,而厌氧氨氧化系统进水中虽然亚硝化出水所占比例为 ABR 除碳系统的 1.5 倍,但是亚硝化出水中  $\text{NO}_2^- - \text{N}$  浓度只有  $35 \text{ mg} \cdot \text{L}^{-1}$  左右,且还存在  $6 \sim 10 \text{ mg} \cdot \text{L}^{-1}$  左右的  $\text{NH}_4^+ - \text{N}$ ,经计算此时厌氧氨氧化进水中  $\text{NO}_2^- - \text{N}$ :  $\text{NH}_4^+ - \text{N}$  浓度为  $0.6 \sim 0.8:1$ ,而目前,学术界普遍接受的厌氧氨氧化反应方程式如式 (1) 所示<sup>[19]</sup>. 从中可知,该反应  $\text{NO}_2^- - \text{N}$  和  $\text{NH}_4^+ - \text{N}$  消耗量的理论比为  $1.32:1$ <sup>[20]</sup>,而本实验厌氧氨氧化系统进水中  $\text{NO}_2^- - \text{N}$  浓度所占比例较小,ANAMMOX 菌长期得不到均衡的基质,故而出水  $\text{NH}_4^+ - \text{N}$  浓度又出现上升的现象.



在一体式反应器运行 37 d 后,将厌氧氨氧化系统进水比例中亚硝化系统出水:ABR 除碳系统出水 (1.5:1) 调整为 2:1. 经计算,此时厌氧氨氧化系统进水  $\text{NO}_2^- - \text{N}$ :  $\text{NH}_4^+ - \text{N}$  浓度为 1:1 左右,基本满足厌氧氨氧化反应所需基质,在之后 40 d 的实验运行中,厌氧氨氧化系统出水即一体式反应

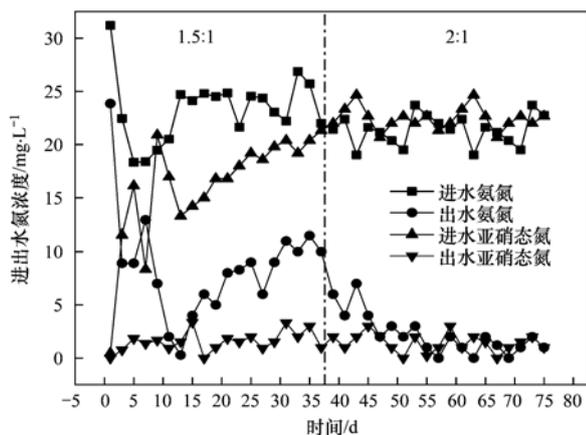


图4 厌氧氨氧化进出水氮浓度变化

Fig. 4 Change of influent and effluent nitrogen concentration during ANAMMOX

器出水  $\text{NH}_4^+ \text{-N}$ 、 $\text{NO}_2^- \text{-N}$  浓度稳定在  $3 \text{ mg} \cdot \text{L}^{-1}$  以下,出水  $\text{NO}_3^- \text{-N}$  浓度在  $4 \text{ mg} \cdot \text{L}^{-1}$  左右,总氮去除率在  $86\% \sim 92\%$ 。

此外,如图5,厌氧氨氧化系统进水经亚硝化系统出水和 ABR 除碳系统出水混合后 COD 浓度在  $60 \sim 80 \text{ mg} \cdot \text{L}^{-1}$ ,出水 COD 浓度在  $20 \sim 40 \text{ mg} \cdot \text{L}^{-1}$ ,有机物并未对厌氧氨氧化产生不良影响。近年来,研究者在有机物对 ANAMMOX 影响方面展开了大量研究<sup>[21~23]</sup>, $150 \text{ mg} \cdot \text{L}^{-1}$  以下有机物浓度可使异养菌与 ANAMMOX 菌共存,并达到相互促进的作用,这也是本实验厌氧氨氧化系统能够稳定运行的原因。

### 2.3 微生物菌群结构变化

利用 MiSeq 高通量测序平台对实验前后亚硝化系统和厌氧氨氧化系统污泥中微生物多样性进行分析,本次研究中4个样品的覆盖度均大于99.99%,可确保本次测序结果能够代表样本中微生物群落组

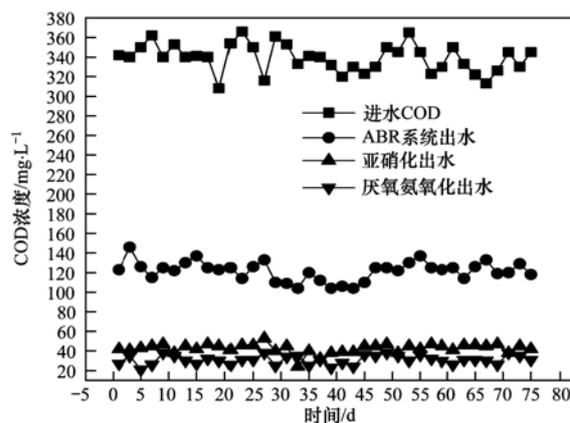


图5 一体式反应器各系统 COD 浓度变化

Fig. 5 Change of COD concentration in different systems of the integrated reactor

成。如表1所示,ACE指数和Chao1指数表征菌群丰度<sup>[24]</sup>,实验后亚硝化系统和厌氧氨氧化系统的Chao1和ACE指数均有所增加,表明实验后亚硝化系统和厌氧氨氧化系统均拥有更高的微生物物种丰度。Shannon指数和Simpson指数表征菌群多样性,Shannon值越大则表征微生物菌群组成复杂程度越高<sup>[25]</sup>,亚硝化系统和厌氧氨氧化系统实验后Shannon指数均略有增加,是因为在一体式ABR除碳-亚硝化-厌氧氨氧化反应器启动过程中,前置系统中有部分微生物随水流至下一系统中,从而造成微生物组成复杂程度变高。而Simpson指数表征生物多样性,Simpson指数越大,则表明优势菌群占微生物量的比重越大,反应器性能提升的重要原因是反应器中功能菌群不断淘汰弱势菌群成为反应器的优势菌群,实验后亚硝化系统和厌氧氨氧化系统Simpson指数均得到提升,这也从微生物角度表征了亚硝化系统和厌氧氨氧化系统功能得到提升。

表1 实验前后微生物多样性变化

Table 1 Variation of microbial diversity before and after the experiment

样品	Chao1 指数	ACE 指数	Shannon 指数	Simpson 指数	覆盖度/%
亚硝化实验前	64	64.07	1.95	0.24	99.99
亚硝化实验后	82.5	84.78	2.01	0.26	99.99
ANAMMOX 实验前	72	73.41	2.81	0.08	99.99
ANAMMOX 实验后	96	94.24	3.05	0.11	99.99

图6为亚硝化系统实验前后各菌群在纲水平上的相对丰度,从中可以看出 $\gamma$ -Proteobacteria纲得到显著提升,而Proteobacteria门几乎涵盖了所有类型的AOB,且 $\gamma$ -Proteobacteria纲包含兼具呼吸、发酵代谢方式的兼性异养菌<sup>[26]</sup>,它们是COD降解的主要参与者,这也从微生物角度解释了亚硝化系统降解COD的原理,且 $\gamma$ -Proteobacteria纲与反硝化密切相关,反硝化菌消耗有机物将亚硝化系统中 $\text{NO}_2^- \text{-N}$ 、

$\text{NO}_3^- \text{-N}$ 氧化为 $\text{N}_2$ ,这也解释了亚硝化系统中存在氮损的原因。Sphingobacteria(鞘脂杆菌纲)数量有所减少,Sphingobacteria纲与分泌EPS有关,这可能与亚硝化污泥接种前后生存环境变化有关,接种前亚硝化污泥所在种泥反应器更容易形成颗粒状,而颗粒污泥与EPS密切相关,故Sphingobacteria纲在实验后有所减少。

如图7,厌氧氨氧化系统实验前后主要菌群均

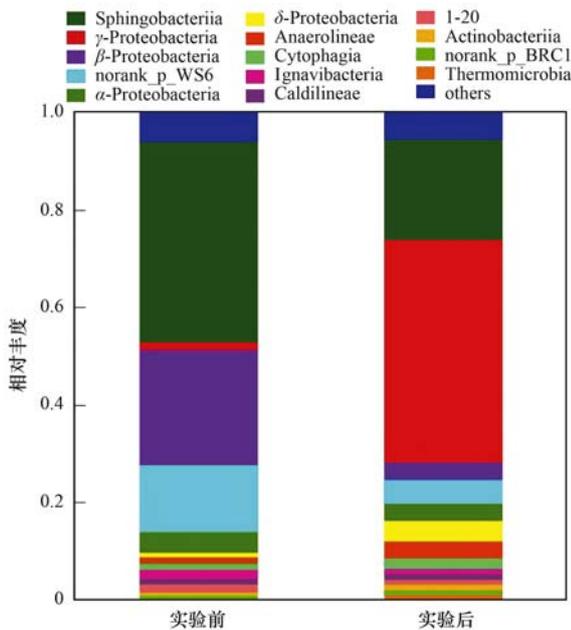


图6 实验前后,亚硝化系统中各菌群在纲级别上的相对丰度  
Fig. 6 Relative abundance of different microbial classes in the nitrification system before and after the experiment

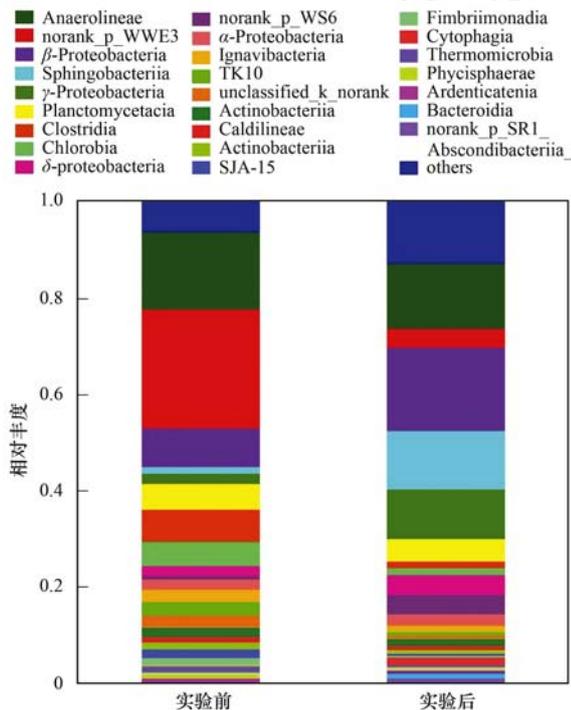


图7 实验前后,厌氧氨氧化系统中各菌群在纲级别上的相对丰度

Fig. 7 Relative abundance of different microbial classes in the ANAMMOX system before and after the experiment

为 Anaerolineae (厌氧绳菌纲)、norank\_p\_WWE3、 $\beta$ -Proteobacteria 和 Sphingobacteriia 纲。Anaerolineae 纲是厌氧生物反应器中常见的微生物菌群,对比实验前,实验后厌氧氨氧化系统中 Sphingobacteriia 纲有显著增加,有研究表明<sup>[27]</sup> Sphingobacteriia 纲具有提高微生物生长速率和脱氮速率的功能,故从微生物

角度解释了实验后厌氧氨氧化系统脱氮性能提高的原因。

### 3 结论

(1)控制亚硝化系统 HRT 为 3h、DO 为 0.8 ~ 1.2  $\text{mg}\cdot\text{L}^{-1}$ , FA 浓度 2 ~ 10  $\text{mg}\cdot\text{L}^{-1}$ ,亚硝化系统出水  $\text{NH}_4^+\text{-N}$  浓度 6 ~ 10  $\text{mg}\cdot\text{L}^{-1}$ ,氨氮去除率 80% ~ 90%, NAR 85% ~ 93%,出水 COD 浓度在 40  $\text{mg}\cdot\text{L}^{-1}$  左右,不会对后续 ANAMMOX 系统产生不良影响。

(2)控制亚硝化系统出水和 ABR 除碳出水比例为 2 : 1 作为厌氧氨氧化系统进水,满足 ANAMMOX 所需  $\text{NO}_2^- \text{-N}$  和  $\text{NH}_4^+ \text{-N}$  基质比 1 : 1 左右。一体式反应器出水  $\text{NH}_4^+ \text{-N}$ 、 $\text{NO}_2^- \text{-N}$  浓度稳定在 3  $\text{mg}\cdot\text{L}^{-1}$  以下,出水  $\text{NO}_3^- \text{-N}$  浓度在 4  $\text{mg}\cdot\text{L}^{-1}$  左右,出水 COD 浓度在 20 ~ 40  $\text{mg}\cdot\text{L}^{-1}$ ,总氮去除率在 86% ~ 92%,COD 去除率 85% 以上,ABR 除碳-亚硝化耦合厌氧氨氧化工艺能够有效用于处理城市污水脱氮除碳。

(3)实验后,亚硝化系统和厌氧氨氧化系统均拥有更高的微生物物种丰度,亚硝化系统中与反硝化密切相关的  $\gamma$ -Proteobacteria 纲有所增加,厌氧氨氧化系统中具有较高微生物生长速率和增强脱氮速率功能的 Sphingobacteriia 纲显著增加,从微生物角度解释了实验后一体式反应器脱氮性能提高的原因。

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