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# 厌氧发酵中微生物与磺胺类抗生素相互影响的研究进展

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## 摘　要

厌氧发酵技术是处理畜禽粪污的有效手段之一。畜禽粪污中含有的多种抗生素，通过影响厌氧发酵菌群的活性，造成发酵系统内有机物含量与组成发生变化，从而影响厌氧发酵的稳定运行，降低产气效率。与此同时，抗生素在厌氧环境下也会被厌氧微生物所降解。本文总结了磺胺类抗生素对厌氧发酵过程中微生物的影响，综述了生物降解磺胺类抗生素的菌群、效果及降解途径，为降低磺胺类抗生素对厌氧发酵效率的影响和提高磺胺类抗生素生物降解效果具有一定的指导意义。

## 关键词

厌氧发酵，微生物，磺胺类抗生素，生物降解

# Research Advances on the Interaction between Microorganisms and Sulfonamide Antibiotics in Anaerobic Fermentation

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## Abstract

**The technology of anaerobic fermentation was one of the effective means to treat livestock manure. A variety of antibiotics contained in livestock manure affected the activity of anaerobic fermentation bacteria, resulting in changes in the content and composition of organic matter in the**

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**fermentation system, which affected the stable operation of anaerobic fermentation and reduced the gas production efficiency. At the same time, antibiotics can be degraded by anaerobic microorganisms in anaerobic environment. This paper summarized the effects of sulfonamide antibiotics on microorganisms in the process of anaerobic fermentation. The degrading bacteria, degradation effect and degradation pathway of sulfonamide antibiotics were reviewed. It had important significance for reducing the impact of sulfonamide antibiotics on anaerobic fermentation efficiency and improving the biodegradation effect of sulfonamide antibiotics.**

## Keywords

**Anaerobic Fermentation, Microorganism, Sulfonamides, Sulfonamide Antibiotics**

## 1. 引言

厌氧发酵技术被广泛应用于畜禽粪污无害化与资源化处理之中[1] [2]。厌氧发酵主要依靠微生物种群之间的相互作用，为保证厌氧发酵稳定运行且有较高的产气效率，提高微生物活性是最有效手段。磺胺类抗生素作为一种广谱抑菌类药物，被广泛应用于畜禽养殖过程中[3]。由于其在动物肠道中的吸附和降解性差，导致大部分磺胺类抗生素随尿液和粪便排出体外，并且不发生任何变化[4]。由于磺胺类抗生素中的磺酰胺基对位氨基($N^4$)上 $R_2$ 基团和磺酰胺基的 $R_1$ 基团与对氨基苯甲酸相似，二者竞争二氢叶酸合成酶，抑制微生物二氢叶酸的合成，影响微生物核酸的生成，从而抑制微生物的生长繁殖[5]。

研究表明，畜禽粪污中的抗生素会降低厌氧发酵产气效率[6]。磺胺类抗生素浓度为 25 mg/L 时，磺胺噻唑和磺胺甲恶唑对生成甲烷的抑制作用在 42%~49% [7]。Cetecioglu 等研究磺胺甲恶唑浓度对厌氧发酵的影响，表明产甲烷量随磺胺甲恶唑浓度的增高而逐渐降低，浓度低于 100 mg/L 时抑制效果不明显；浓度在 100~250 mg/L 时抑制效果明显，甲烷产量明显降低；超过 250 mg/L 时厌氧环境失衡，无甲烷产生[8]。但 Mitchell 等考察 4 种抗生素对产气量的影响，其中磺胺二甲基嘧啶浓度达到 280 mg/L 时，对产气量依旧没有影响[9]。说明不同种类的磺胺类抗生素对厌氧发酵过程中微生物的活性影响不同。

另外，磺胺类抗生素存在于环境会引起一系列的危害，尤其是会增加细菌抗药性，威胁人类身体健康[10]。因此，研究磺胺类抗生素的去除方法成为研究热点，其中生物降解由于其价格低廉、二次污染少等优点被广泛研究。本研究梳理了厌氧发酵中主要功能微生物，通过阐述磺胺类抗生素对厌氧微生物的影响，分析磺胺类抗生素对厌氧发酵的影响机理。另外，通过归纳总结磺胺类抗生素降解菌群、降解效果及降解途径，为在天然生态系统和工程生态系统中原位或异位降解磺胺类抗生素提供技术和数据支撑。

## 2. 磺胺类抗生素对厌氧发酵微生物的影响

厌氧发酵过程需要水解、产酸、产氢和产甲烷菌的共同参与，包含细菌和古菌两种。但磺胺类抗生素对细菌和古菌的影响却不同，某些磺胺类抗生素可通过抑制细菌的核糖体蛋白合成过程来阻止细菌繁殖[11]。而古菌由于其核糖体由不均一的蛋白质组成，故对磺胺类抗生素有较高的耐受性[12]。

## 2.1. 对厌氧细菌的影响

细菌主要参与厌氧发酵中水解和酸化阶段，其主要功能和分类如图 1 所示。

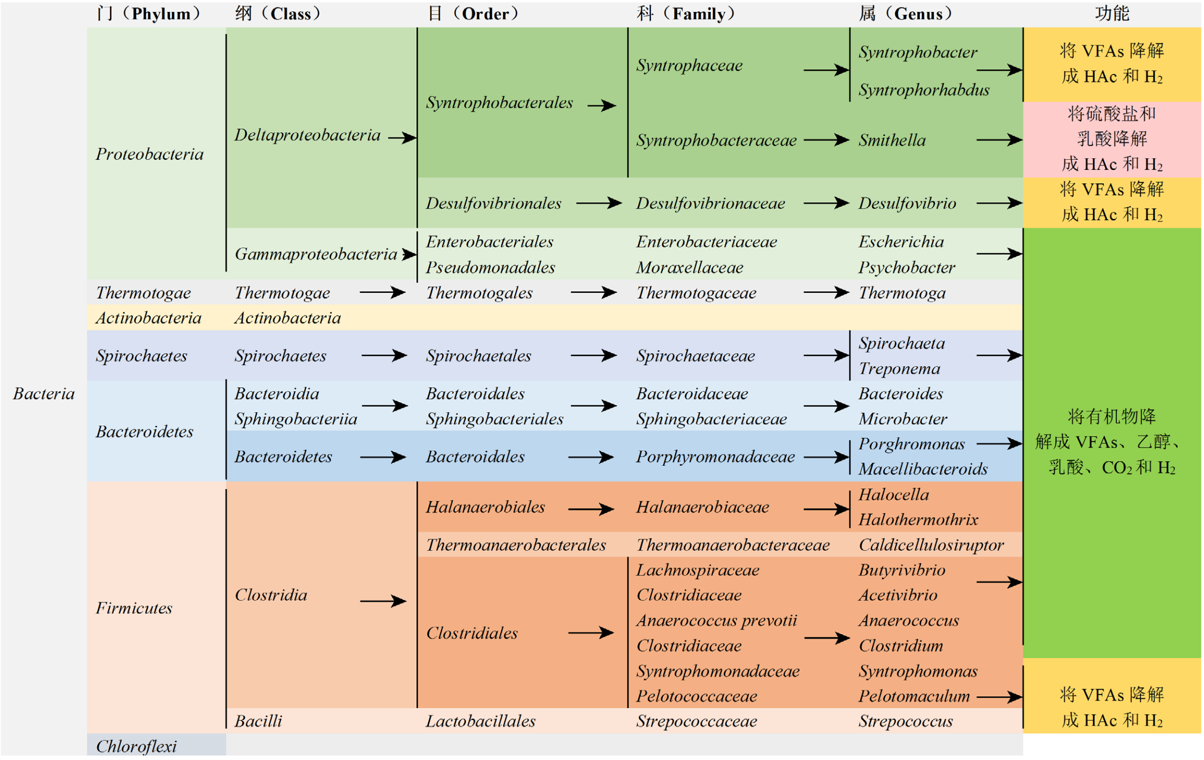


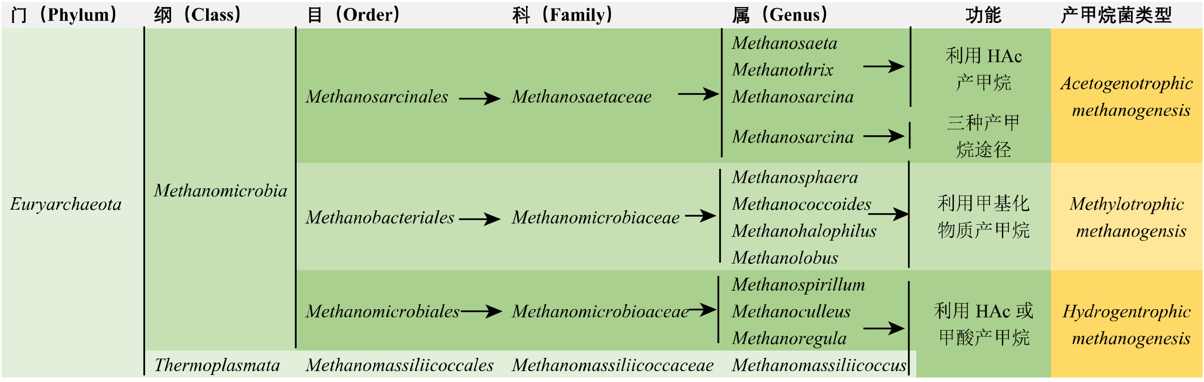
**Figure 1.** Classification and main functions of bacteria in anaerobic fermentation
**图 1.** 细菌在厌氧发酵中分类与主要功能

参与厌氧发酵的细菌主要包括 *Thermotogae*、*Actinobacteria*、*Spirochaetes*、*Bacteroidetes* 和 *Firmicutes* 菌门。Cetecioglu 等[13]发现 *Firmicutes* 菌门中的 *Clostiridum* 菌属可降解大分子有机物，并产生乳酸、乙醇和挥发性脂肪酸。*Clostiridum* 菌属丰度不受环境中磺胺甲恶唑的影响，*Acinetobacter* 的丰度随着磺胺甲恶唑浓度的增加而变大，说明磺胺甲恶唑对各种细菌的影响不同，从而影响水解和产酸过程[13]。Aydin 等[11]证明抗生素会对 *Bacteroidetes*、*Acinetobacter* 和 *Proteobacteria* 菌门会产生负面影响，且抑制作用与抗生素浓度有关，但当环境中抗生素浓度达到 3.0 mg/L 时，*Firmicutes* 丰度无显著变化。

抗生素对丙酸和丁酸等挥发性脂肪酸的降解有一定抑制作用，通过抑制相关微生物活性来实现，包括 *Syntrophomonas*、*Syntrophospora*、*Syntrophobacter* 和 *Pelotomaculum* 等。Aydin 等[12]证明挥发性有机酸的利用受抗生素的抑制，其中抗生素对利用丙酸的细菌的抑制作用高于利用丁酸的细菌。Bauer 等[14]研究表明低浓度的抗生素对微生物群落结构影响不大，增加抗生素浓度会降低微生物多样性。Wang 等[15]研究 4 种磺胺类抗生素对厌氧细菌的影响，结果表明磺胺甲恶唑的抑制作用最小，磺胺喹噁啉的抑制作用最大。

## 2.2. 对厌氧古菌的影响

参与厌氧发酵过程的古菌种类以产甲烷菌为主，其在厌氧发酵过程中的分类和主要功能，如图 2 所示。在产甲烷阶段，抗生素通过影响嗜酸(*Acetogenotrophic methanogenesis*)、嗜甲基化合物(*Methylotrophic* *methanogenesis*)和嗜氢产甲烷菌(*Hydrogentrophic methanogenesis*)3 种类型的产甲烷菌群结构，影响整个产甲烷过程。



| 门（Phylum） | 纲（Class） | 目（Order） | 科（Family） | 属（Genus） | 功能 | 产甲烷菌类型 |
|---|---|---|---|---|---|---|
| *Euryarchaeota* | *Methanomicrobia* | *Methanosarcinales* | *Methanosaetaceae* | *Methanosaeta*<br>*Methanothrix*<br>*Methanosarcina* | 利用 HAc 产甲烷 | *Acetogenotrophic methanogenesis* |
| | | | | *Methanosarcina* | 三种产甲烷途径 | |
| | | *Methanobacteriales* | *Methanomicrobiaceae* | *Methanosphaera*<br>*Methanococcoides*<br>*Methanohalophilus*<br>*Methanolobus* | 利用甲基化物质产甲烷 | *Methylotrophic methanogensis* |
| | | *Methanomicrobiales* | *Methanomicrobioaceae* | *Methanospirillum*<br>*Methanoculleus*<br>*Methanoregula* | 利用 HAc 或甲酸产甲烷 | *Hydrogentrophic methanogenesis* |
| | *Thermoplasmata* | *Methanomassiliicoccales* | *Methanomassiliicoccaceae* | *Methanomassiliicoccus* | | |

**Figure 2.** Classification and main functions of Archaea in anaerobic fermentation
**图 2.** 古菌在厌氧发酵中分类与主要功能

抗生素的种类和浓度是引起古菌微生物种群丰度发生变化的因素。厌氧反应器中抗生素会抑制嗜酸产甲烷菌的生长繁殖，但却能促进嗜氢产甲烷菌的生长繁殖，使其丰度增加。当系统中存在 40 mg/L 的磺胺甲恶唑时，嗜氢产甲烷菌占主导地位，*Methanobacterium* 和 *Methanogenic archeons* 的丰度增加，但会引起嗜酸产甲烷菌的丰度降低[11]。

但根据大量文献报道[11] [13] [16]，在长期接触高浓度混合抗生素的厌氧系统中，产甲烷菌的总量不受影响。因为嗜氢产甲烷菌对高浓度抗生素有较高的耐受性，具有更高的底物利用率、生长率和细胞繁殖能力，所以大部分产甲烷菌以嗜氢产甲烷菌的形式存在，即使嗜酸产甲烷菌丰度降低，但却不会引起产甲烷菌总量的降低[17]。厌氧系统中嗜氢产甲烷菌活性增大，能快速将乙酸转化为氢气和二氧化碳，为嗜氢产甲烷菌产甲烷提供了底物。因此，嗜氢产甲烷菌和嗜酸产甲烷菌互补的存在使系统保持稳定[13]。

## 3. 磺胺类抗生素的生物降解

### 3.1. 磺胺类抗生素的降解菌

#### 3.1.1. 降解菌株

环境中存在大量能降解磺胺类抗生素的微生物，前人从长期驯化后的活性污泥、受抗生素污染的土壤和粪便中分离出大量可降解磺胺类抗生素的菌株(如表 1 所示)。一些菌株能利用磺胺类抗生素作为唯一碳源进行生长繁殖，并达到降解的目的，一些菌株经驯化后对磺胺类抗生素有一定的降解作用[18] [19]。

生物降解磺胺类抗生素的效果与环境中营养物质的组成与含量有关，环境中存在易降解的碳源和氮源，能促进微生物对磺胺类抗生素的降解。研究证明，从长期处理含磺胺类抗生素废水的生物膜反应器中分离出的 *Microbacterium* sp. BR1 菌株，能利用磺胺甲恶唑作为唯一碳源进行生长繁殖[20]。通过改变碳源和氮源(维生素和酵母提取物)的含量，能进一步提高磺胺甲恶唑的降解速率，说明生物降解磺胺甲恶唑可与其他有机物存在共代谢的机制。另外，磺胺嘧啶和磺胺甲恶唑在接种 *Microbacterium* sp. BR1 的环境下培养 24.5 h 可以完全被降解，故 *Microbacterium* sp. BR1 是一种磺胺类抗生素的高效降解菌株[21]。

从驯化后的活性污泥和废水中可分离出降解磺胺类抗生素的菌株，磺胺甲恶唑的降解率可达 100%，并且能以磺胺类抗生素作为单一碳源进行生长繁殖[30]。当环境中存在琥珀酸盐和乙酸盐时，菌株利用共代谢机制可提高磺胺甲恶唑的降解效果，并且高浓度(mg/L)磺胺类抗生素也可被完全降解[30]。从含磺胺

类抗生素的土壤中分离出的微生物菌株(SDZm4 和 sp.C448)可以完全降解磺胺嘧啶和磺胺甲恶唑，且其降解效率随外加碳源的增加而增大[4] [31]。Islas 等[32]分离出一种 *Pseudomonas* 菌属，能以磺胺甲恶唑为唯一碳源，降解率为 0.2%~1.5%。*Acinetobacter* 菌属被证明是磺胺类抗生素降解菌，其中 *Acinetobacter* sp. HS51 在 2 d 内可降解 67%的磺胺噻唑；*Acinetobacter* W1 在 24 h 内可降解 95%~100%的磺胺甲恶唑，且在 pH 为 7.0，温度 25℃时降解效果最佳[25]。*Rhodococcus equi* 不能以磺胺类抗生素为单一碳源，存在葡萄糖等有机物时，磺胺甲恶唑的降解率可达 29%，存在其他微生物时降解效果降低[33]，说明降解菌之间存在竞争。另外，由于磺胺类抗生素具有抑菌作用，随着初始浓度的增加其生物降解效果存在降低情况[34]。

**Table 1.** Degradation strains of some sulfonamide antibiotics and their degradation effects
**表 1.** 部分磺胺类抗生素的降解菌株及其降解效果

| 来源 | 菌株名称 | 试验条件 | 去除率 |
|---|---|---|---|
| 活性污泥 | *Microbacterium* sp. BR1 | MSM；127 mg/L 磺胺甲恶唑 | 24%~44% [20] |
| | *Microbacterium* sp. BR1 | MSM；0.5 mg/L 酵母提取物；0.5 mg/L 维生素；127 mg/L 磺胺甲恶唑、磺胺嘧啶 | 100% [21] |
| | *Brevundimonas* sp. SMXB12 | MSM；10 mg/L 磺胺甲恶唑 | 100% [22] |
| | *Pseudomonas psychrophila* HA-4 | MSM；100 mg/L 磺胺甲恶唑；10℃ | 34.3% [20] |
| | *Achromobacter denitrificans* PR1 | MSM；0.5 g/L 硫酸铵；150 mg/L 磺胺甲恶唑 | 99%~100% [23] |
| | *Arthrobacter* sp. D2 | MSM；50 mg/L 磺胺嘧啶；2 g/L 葡萄糖 | >82% [24] |
| | *Acinetobacter* sp. W1 | MSM；40 mg/L 磺胺甲恶唑；5 mg/L 溶解氧 | 100% [25] |
| 猪粪 | *Paracoccus* sp. SDZ-PM2-BSH30 | 0.04%酵母提取物；5 mg/L 磺胺嘧啶 | 50% [26] [27] |
| 水/沉积物 | *Pseudomonas* sp. DX7 | MSM；10 mg/L 磺胺嘧啶 | 20%~30% [28] |
| | *Escherichia* sp. HS21 | MSM；10 mg/L 磺胺噻唑；2.5 g/L 蛋白胨 | 45% [29] |

注：MSM 为无机盐培养基。

### 3.1.2. 降解菌群

磺胺类抗生素的存在会影响微生物的群落结构，但微生物也会降解部分磺胺类抗生素。研究证明从水、土壤和沉积物等多种自然环境中发现能降解磺胺类抗生素的菌群，如表 2 所示。

**Table 2.** Degradation bacteria and degradation effects of some sulfonamide antibiotics
**表 2.** 部分 SAs 的降解菌群及其降解效果

| 来源 | 菌群名称 | 试验条件 | 去除效果 |
|---|---|---|---|
| 土壤 | *Pseudomonas* | 200 mg/kg SAs | 42%~100% [35] |
| 活性炭 | *Firmicutes*、*Bacteroidetes* | MSM；5℃~45℃；100 µg/L 磺胺甲氧嘧啶；1 mg/L 葡萄糖 | 14%~90% [36] |
| 活性污泥 | *Achromobacter*、*Pseudomonas* | 厌氧污泥；20~200 mg/L 磺胺甲恶唑 | 100% [35] |
| | *Clostridia*、*Bacteroidia* | 厌氧污泥；0.8 mM 磺胺甲恶唑 | 83% [37] |
| 水/沉积物 | *Bacillus* | 1~100 mg/L 磺胺甲恶唑；0~30 mg/L 腐殖质；25℃ | 0%~40% [38] |

注：MSM 为无机盐培养基。

土壤中筛选出可降解磺胺类抗生素的菌群有 *Firmicutes*、*Proteobacteria*、*Bacteroidetes* 和 *Acidobacteria*。*Firmicutes* 和 *Bacteroidetes* 菌门中的 *Bacillus* 和 *Chryseobacterium* 菌属被证明是降解磺胺甲氧嘧啶的主要菌群[32]。活性污泥中发现大量可降解磺胺类抗生素的优势菌群，包括 *Micrococcus luteus*、*Rhodopirellula baltica*、*Oligotropha carboxidovorans*、*Methylibium petroleiphilum*、*Delftia acidovorans*、*Pseudomonas* 和 *Acinetobacter* [35]。另外，利用微生物燃料电池降解磺胺类抗生素的反应器，从其阳极室筛出两种降解磺胺甲恶唑的优势菌群，分别为 *Pseudomonas* 和 *Achromobacter*，其对磺胺甲恶唑的降解能力较强[39]。在自然和人为环境中，不是所有磺胺类抗生素的降解菌株都能被分离鉴定，大部分以菌群形式被鉴定。

### 3.2. 磺胺类抗生素的生物降解效果

微生物降解磺胺类抗生素的效果与细菌种类、底物初始浓度、pH 和温度等因素有关[40] [41]。通过大量文献总结，厌氧微生物比好氧微生物对磺胺类抗生素有更高的降解效果，其降解效果如表 3 和表 4 所示。Cao 等[42]研究底物初始浓度、外加碳源、pH 和温度对磺胺甲恶唑降解的影响，发现中性 pH，温度 25℃和 0.2 g/L 乙酸钠的环境下，磺胺甲恶唑降解效果最佳。大型污水处理厂在运行过程中也能去除部分磺胺类抗生素，其去除效果与处理工艺和废水成分有关，去除效果从 0~100%不等[43]-[48]。常红等[43]研究北京市 6 家污水处理厂对磺胺类抗生素的降解，其中磺胺甲恶唑、磺胺吡啶、磺胺嘧啶在好氧区和缺氧区被部分降解，在厌氧区被进一步去除，故厌氧去除率较高。

**Table 3.** Aerobic biodegradation and degradation effects of sulfonamide antibiotics
**表 3.** 磺胺类抗生素的好氧生物降解及其效果

| 反应系统 | 试验条件 | 时间 | 去除效果 |
|---|---|---|---|
| 活性污泥 | 3.76 mg/L 磺胺甲恶唑磺；溶解氧 5 mg/L；20℃ | 28 d | 4% [49] |
| | 污水，100 μg/L 磺胺类抗生素 | 10 d | 磺胺嘧啶 53.4%；<br>磺胺甲恶唑 22.6% [50] |
| | 100 μg/L 磺胺类抗生素；2.56 g/L MLSS | 11~13 d | 100% [51] |
| | SBR，1~10 mg/L 磺胺甲恶唑 | 24 h | 46% [52] |
| 土壤 | 1~100 μg/g 磺胺甲恶唑 | 40 d | 78% [53] |
| | 10 mg/kg 磺胺嘧啶；含水率 50%；25℃ | 49 d | 89.6%~97.3% |
| | 1~25 mg/kg 磺胺嘧啶；含水率 50%；25℃ | 15 d | >50% [54] |
| | 土壤 + 粪便，1.5~14 μmol/L | 30 d | 38%~42% [55] |
| 水/沉积物 | 地表水，10 μg/L 磺胺甲恶唑；20℃ | 11 d | 75% [56] |
| | 河水，1~100 mg/L 磺胺甲恶唑 | 40 d | 40%~90% [38] |
| | 河水，10 mg/L 磺胺类抗生素；22℃ | 半衰期：磺胺嘧啶 29.3~46.2 d、磺胺二甲氧嘧啶 25.8~34.9 d、磺胺甲恶唑 50.3~71.2 d、磺胺噻唑 22.4~25.3 d [57] | |

通过研究实验室规模的磺胺类抗生素厌氧生物降解，发现厌氧间歇反应器中磺胺类抗生素的降解率为 22%~100% [26] [58]。磺胺甲恶唑的降解发生在缺氧和好氧区，而磺胺嘧啶主要在厌氧或缺氧区被消除[43]，所以厌氧降解表现出优越性。其降解效果与其初始浓度有关，在厌氧硫酸盐还原菌污泥系统中，磺胺类抗生素浓度在 μg/L 以下时，降解效果遵循拟零级动力学模型，降解速率可达 13.2 ± 0.1 mg/L·d [58]，浓度增大降解速率明显降低[59]。

**Table 4.** Anaerobic biodegradation and degradation effects of sulfonamide antibiotics
**表 4.** 磺胺类抗生素的厌氧生物降解及其效果

| 反应系统 | 试验条件 | 去除效果 |
|---|---|---|
| 活性污泥 | ASBR；1~40 mg/L 磺胺甲恶唑；2250 mg/L COD | 6%~99% [59] |
|  | 5~50 mgN/L·d；50 mgCOD/L·d；172 μg/L 磺胺甲恶唑 | 10%~60% [60] |
|  | 100 μg/L 磺胺类抗生素 | 62%~78% [61] |
| 水/沉积物 | 水力停留时间 8~24 h；有机负荷率 1~9 kgO$_2$/m$^3$·d；10 μg/L 磺胺甲恶唑 | 22%~75% [26] |
|  | 50 mg/L 磺胺类抗生素；24℃ | 半衰期 7~165 d [62] |
|  | 10 mg/kg 磺胺类抗生素；25℃ | 半衰期 10~79 d [63] |
|  | 0.02~263 mg/L 磺胺二甲氧嘧啶；12℃ | 40%~50% [64] |
| 发酵/堆肥 | 发酵；2~10 mg/kg 磺胺类抗生素；37℃ | 0%磺胺噻唑~100%磺胺嘧啶、磺胺二甲氧嘧啶、磺胺甲恶唑[65] |
|  | 堆肥；0~10 mg/L 磺胺类抗生素；25℃~55℃；14 d | 61%~90% |
|  | 发酵；50 mg/kg 磺胺类抗生素；41.7℃；33 d | 磺胺嘧啶 17%~34% [66]<br>磺胺甲恶唑、磺胺甲氧哒嗪 47%~48%；<br>磺胺嘧啶 0% [67] |
|  | 发酵；37℃；10 μg/L 磺胺类抗生素；水力停留时间 15~20 d | 磺胺嘧啶 90%；<br>磺胺氯吡啶 72.8%~90.3% [68] |

大型污水处理厂中的厌氧环节也可以去除磺胺类抗生素。其中，水力停留时间、底物浓度等对降解效果有影响，磺胺甲氧哒嗪的降解效果与 COD 去除率呈正相关关系，表明厌氧降解磺胺甲氧哒嗪也存在共代谢机制[61]。Zhang 等[69]证明水力停留时间是影响磺胺嘧啶去除率的关键，水力停留时间为 17 h 时，磺胺嘧啶去除率达到 23.8%。

厌氧发酵和堆肥也是去除磺胺类抗生素的有效途径[70]。研究发现，中温厌氧发酵可有效去除磺胺类抗生素，硫酸盐和产甲烷的还原环境有利于磺胺嘧啶的生物转化，而添加电子供体受体对其影响不大[64]。厌氧发酵底物中存在大量易被降解的有机物，会造成磺胺类抗生素的降解效果降低[64]，而且磺胺噻唑和磺胺邻二甲氧嘧啶在发酵实验中去除效果不明显[71] [72]。

## 3.3. 磺胺类抗生素的生物降解途径

目前，关于磺胺类抗生素代谢途径的大量研究已经被发表。其生物降解中间产物主要是通过羟基化、乙酰化及 C-N/S-N 键断裂生成。常见的磺胺甲恶唑降解产物为对氨基苯磺酰胺、羟基-N-(5-甲基-1，2-恶唑-3-基)苯-1-磺酰胺、苯胺、3-氨基-5-甲基异恶唑、N$^4$-羟基-SMX(HO-SMX)、4-氨基苯硫酚和 N$^4$-乙酰基-SMX。对氨基苯磺酰胺是磺胺类抗生素固有的降解产物之一，降解途径有两种：N-C 键和 S-N 键的断裂。N$^4$-乙酰-SMX 是磺胺甲恶唑在 N$^4$ 位置发生取代反应所形成，但性质不稳定，易转化回母体化合物[46]。磺胺嘧啶的主要中间产物为 2-氨基嘧啶和 4-羟基-2-氨基嘧啶。*Microbacterium* 利用还原态-还原型辅酶 I 将磺胺嘧啶降解为 2-氨基嘧啶[73]。由于嘧啶环稳性的，大部分磺胺嘧啶能生成等摩尔量的 2-氨基嘧啶。然后被 *Arthrobacter* 和 *Terrabacter* 转化为 4-羟基-2-氨基嘧啶[24]。WANG 等[74]证明磺胺喹噁啉、磺胺对甲氧嘧啶和磺胺噻唑均可发生乙酰化、羟基化和葡萄糖醛酸化反应，其取代反应主要发生在 N$^4$ 或 N$^1$ 氨基部分。

## 4. 研究展望

目前，对磺胺类抗生素生物降解效果与机理的研究主要以磺胺甲恶唑和磺胺嘧啶为主，且其机理研究主要局限在实验室阶段，以后的研究需在以下方面加强：

1) 磺胺类抗生素的生物降解机理。磺胺抗生素的降解与多种因素有关，而厌氧发酵过程复杂也会影响其降解效果。因此，展开厌氧发酵不同阶段内磺胺类抗生素降解效果的研究，将为厌氧去除抗生素提供更有利的理论依据。

2) 厌氧微生物的作用机理。厌氧发酵过程中涉及多种微生物，磺胺类抗生素的抑菌作用对某些微生物会产生不利影响，但有些微生物却能降解磺胺类抗生素。根据现有研究，明确微生物种类和作用，可提高厌氧发酵效率的同时增大磺胺类抗生素的去除效果。

3) 多种抗生素存在的降解效果。本文主要总结了磺胺类抗生素的降解菌、降解效果和降解机理，但环境中存在其他类抗生素也会产生环境危害。研究并总结四环素类、大环内酯类和喹诺酮类等抗生素对环境的影响及其降解机理也具有重大意义。

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