

专论与综述

基于群体感应效应的 MBR 膜污染控制原理、实现途径及微生态响应

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摘要: 膜污染是膜生物反应器(membrane bioreactor, MBR)在工程实践应用中难以避免的挑战性问题, 严重限制该工艺的经济性和环境友好性。MBR 系统中的膜污染形成过程涉及物理、化学和生物等多种机制, 受到膜材料特征、混合液特征、系统运行参数和进水水质特征等多方面因素影响, 其中主要由微生物形成生物膜而导致的生物污染对膜污染贡献巨大。基于群体感应效应(quorum sensing, QS)对生物膜形成的重要作用, 通过人工干预手段阻断 QS 调控通路的群体感应淬灭(quorum quenching, QQ)策略成为从源头上控制 MBR 膜污染的新技术途径。QQ 策略以筛选出的高活性 QQ 化合物、QQ 酶和 QQ 菌为基础, 通过开发基于海藻酸钠、高分子复合材料、二氧化硅及膜材料表面化学修饰等不同形式和结构的固定化技术, 可实现对 MBR 膜污染进程的显著延缓, 使膜污染周期最高可延长 10 倍, QQ 活性维持时间可长达 160 d 以上。QQ 策略还对 MBR 系统微生物群落产生显著影响, 可改变与膜污染形成相关物种的相对丰度以及群落多样性和物种互作模式。为促进 QQ 策略的实际应用, 未来还应精准识别复杂条件下 QS 对膜污染形成的调控作用, 深入解析微生物群落结构和功能对 QQ 的响应规律, 创新研发可以应对各种不利因素的高性能 QQ 固定化载体材料。

关键词: 膜污染; 群体感应效应; 群体感应淬灭; 固定化载体; 微生物群落

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Quorum sensing-based fouling control in membrane bioreactors: mechanisms, strategies, and microbial ecological responses

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Abstract: Membrane fouling is an unavoidable and challenging issue in the engineering application of membrane bioreactors (MBRs), significantly limiting the economic and environmental benefits of this technology. The fouling formation processes in MBRs involve a range of physical, chemical, and biological mechanisms. They are influenced by multifaceted factors such as membrane properties, mixed liquor characteristics, operating parameters, and influent quality. A major contributor to MBR fouling is biofilm formation, primarily driven by microbial coordinate behaviors. Due to the key role of quorum sensing (QS) in regulating biofilm formation, quorum quenching (QQ), a strategy that disrupts normal QS pathways, offers a novel approach to inhibit biofouling at its source. The implementation of QQ-based control involves the selection of highly active QQ compounds, enzymes, and bacteria. These agents are applied through various immobilization techniques, such as incorporation into sodium alginate, polymer composites, and silica or chemical modification of the membrane material surface. These approaches have demonstrated significant success in delaying fouling processes in lab-scale MBRs, which could extend the membrane fouling cycle by up to 10 times and maintain QQ activity for over 160 d. Additionally, QQ strategies can alter the relative abundance of bacterial taxa associated with fouling formation, community diversity, and interspecies interaction patterns, thereby leading to the shift of microbial community structures within MBRs. To promote the practical application of QQ strategies, future work should focus on accurately identifying the role of QS in membrane fouling under complex conditions, understanding the microecological responses to QQ, and developing high-performance QQ immobilization media that can withstand various adverse factors.

Keywords: membrane fouling; quorum sensing; quorum quenching; immobilization media; microbial community

膜生物反应器(membrane bioreactor, MBR)是一种将膜分离技术和活性污泥生物降解过程相结合的污水处理与回用工艺。相对于传统的活性污泥法处理工艺, MBR 具有一些显著优势: (1) 高效截留微生物, 实现污泥停留时间(sludge retention time, SRT)和水力停留时间(hydraulic retention time, HRT)的分离, 有利于富集功能微生物, 提升污染物去除效能; (2) 固液分离效率高, 出水水质良好且稳定, 剩余污泥产量低; (3) 系统集成度高, 占地面积

小, 运行管理自动化程度高^[1-2]。经过 30 余年的发展, MBR 工艺已经在全球各类污水处理工程中获得广泛应用^[3-4]。从城市生活污水、普通工业废水, 到高浓度、难降解的工业废水, 如化工废水、造纸废水、印染废水和制药废水等^[5-6], 都能见到 MBR 工艺的实践。2006 年, 中国第一座大型 MBR 污水处理厂(处理能力超过 $1 \times 10^4 \text{ m}^3/\text{d}$)在北京市密云区建立; 2010 年, 我国大型 MBR 系统的总处理能力达到 $1 \times 10^6 \text{ m}^3/\text{d}$; 2017 年达到 $1 \times 10^7 \text{ m}^3/\text{d}$; 2020 年,

我国大型 MBR 处理系统总数超过 300 座, 总处理能力超过 $1.7 \times 10^7 \text{ m}^3/\text{d}$, 其中约 75% 用于城市污水处理, 占全国城市污水处理总量的 9%^[7-8]。由此可见, 我国 MBR 工艺的投产应用始终保持快速增长的趋势, 近年来各地污水处理厂的提升改造也将 MBR 作为工艺升级的优先选项。

尽管 MBR 工艺具有上述优势且应用广泛, 但其在工程实践过程中也面临一个挑战性问题——膜污染(membrane fouling)。膜污染的存在大幅增加了 MBR 系统在运行和维护中的能源和资源消耗, 严重限制了 MBR 工艺的经济性和环境友好性。为维持正常的膜过滤通量, MBR 工程实践中一般采用物理和化学的膜污染控制措施, 但其能耗成本较高^[4]。例如, 在 MBR 好氧单元采用强化曝气冲刷可缓解膜材料表面的膜污染, 但该方法所产生的费用占总运行成本的 35%–50%^[9]; 另有研究估算出大型 MBR 系统的能源消耗占总运行成本的 40%–60%, 其中相当一部分是用于膜污染清洗^[7]。虽然通过维护性的在线清洗和恢复性的离线清洗会减缓膜污染, 但并不能从根源上抑制膜污染的形成, 并且化学清洗也会缩短膜的使用寿命、影响系统内微生物活性并造成二次污染^[4,10]。因此, 膜污染是制约 MBR 工艺可持续发展 and 得到更广泛应用的关键因素, 亟须探索和建立更高效、更经济、更绿色的技术方案来解决膜污染问题。

近年来, 微生物的群体感应效应(quorum sensing, QS)被证明在 MBR 膜污染形成过程中发挥了重要作用。在此基础上, 采用可干扰或阻断群体感应效应的群体感应淬灭(quorum quenching, QQ)策略成为一种可从源头控制 MBR 膜污染的新技术途径, 受到研究广泛关注。尽管国内外已有针对相关研究的综述^[11-15], 但部分综述已发表数年, 并且对 QQ 菌和 QQ 应用形式的梳理不够系统, 也较少关注 QQ 对 MBR 微生物群落的影响。随着新研究的加速涌

现, 特别是 QQ 菌资源库不断扩充、新型应用方式不断开发、微生物群落研究方法不断深入, 亟须对这些研究内容进行更全面系统的展示和论述。本文系统综述了利用 QQ 策略控制 MBR 膜污染的最新研究进展, 包括该策略的基本原理、具体材料、技术路径及其对 MBR 系统微生物群落的影响, 以期为膜污染控制新技术和理论的发展提供更全面的科学参考。

1 MBR 膜污染的形成机制与主要类型

1.1 膜污染的形成机制和影响因素

MBR 膜污染是指反应器混合液中的悬浮颗粒(包括微生物细胞及其裂解碎片等)、胶体粒子、溶解性有机物或无机盐等, 由于和膜材料之间存在各类相互作用而在膜表面上吸附与沉积, 或在膜孔内吸附, 造成膜孔径变小或膜孔堵塞, 从而导致膜的过滤性能下降、水通过膜的阻力增加, 最终表现为膜通量(membrane flux)显著下降或跨膜压差(transmembrane pressure, TMP)急剧升高的现象^[16]。MBR 膜污染形成的一般过程如图 1A 所示, 其形成机制包括膜孔堵塞(pore clogging)、生物膜形成(biofilm formation)、滤饼层形成(cake layer formation)、浓差极化(concentration polarization)等复杂过程^[17]。

膜孔缩窄和堵塞是膜污染形成的最初阶段, 即溶解性的无机或有机化合物沉积、吸附在膜孔内部, 悬浮颗粒或胶体粒子进入膜孔也会发生吸附并逐渐填满膜孔; 当距离较近的膜孔均被填满后, 污染物会逐渐接触并在膜表面连成一片; 溶解性微生物产物(soluble microbial product, SMP)和胞外聚合物(extracellular polymeric substance, EPS)等微生物代谢产物逐渐积累并覆盖在膜表面, 促进微生物和胶体的进一步附着, 生物膜也随之形成, 这些物质不断堆积并最终形成滤饼层^[18]; 随着滤饼层的厚度增加、孔隙率不断下降, 膜表面部分区域的

局部通量超过临界通量(critical flux)时, TMP 会出现跳跃式上升, 从而快速达到膜污染周期的终点, 之后必须进行清洗操作才能恢复膜通量^[19]。此外, 在膜过滤过程中, 大分子物质和固态颗粒物质不断在膜表面累积, 使膜表面的溶质浓度高于混合液主体的溶质浓度, 产生浓差极化现象, 从而进一步增加膜过滤阻力^[20-21]。

MBR 膜污染是在多重复杂因素影响下由不同物理、化学和生物机制综合作用而形成的。如图 1B 所示, 膜材料特征(膜材质、表面电荷、亲疏水性、形貌模式等)、混合液特征(污泥浓度、污泥絮体粒径、SMP、EPS、微生物群落、生物膜形成等)、系统运行参数(HRT、SRT、操作模式、曝气强度等)、进水水质特征(碳氮比、污泥负荷、盐度、毒性、特征污染物等)等 4 个方面的多种因素^[4,16,22-23]都会影响 MBR 膜污染的形成, 这也导致要实现膜污染的有效控制变得十分困难。长期以来, 膜污染始终是环境工程、材料科学、微生物学等交叉学科研究领域的热点, 研究和技术人员一方面深入探究不同因素对膜污染形成的影响程度和机制, 另一方面也从这些影响因素

出发提出针对性的膜污染控制手段和策略。

1.2 膜污染的主要类型

膜污染是膜材料和污水中的化学或生物成分在一定条件下相互作用的复杂产物, 可根据相应的标准将其分为不同的类型。按照清洗可恢复性可以将膜污染分为可逆污染(暂时性污染)、不可逆污染(长期性污染)和不可恢复污染(永久性污染)^[24]: 可逆污染是指通过物理清洗的手段如机械振动、强化曝气或反冲洗等就可以去除的污染, 一般是指膜表面较厚的滤饼层; 不可逆污染是指物理清洗不能有效去除而需要化学试剂清洗才能去除的污染, 一般是指膜表面的滤饼层和膜孔内的轻微堵塞; 不可恢复污染是指采用任何类型的清洗手段都无法去除的顽固污染, 其直接缩短膜组件的使用寿命。

按照污染物的性质和形成机制可以将膜污染分为无机污染、有机污染和生物污染三大类^[25]。

(1) 无机污染, 指溶解性无机盐等物质在溶剂中因为溶剂性质(如 pH、温度等)的改变而发生氧化还原等化学反应, 以沉淀的形式沉积于膜表面或膜孔内, 也被称为矿物质沉积。

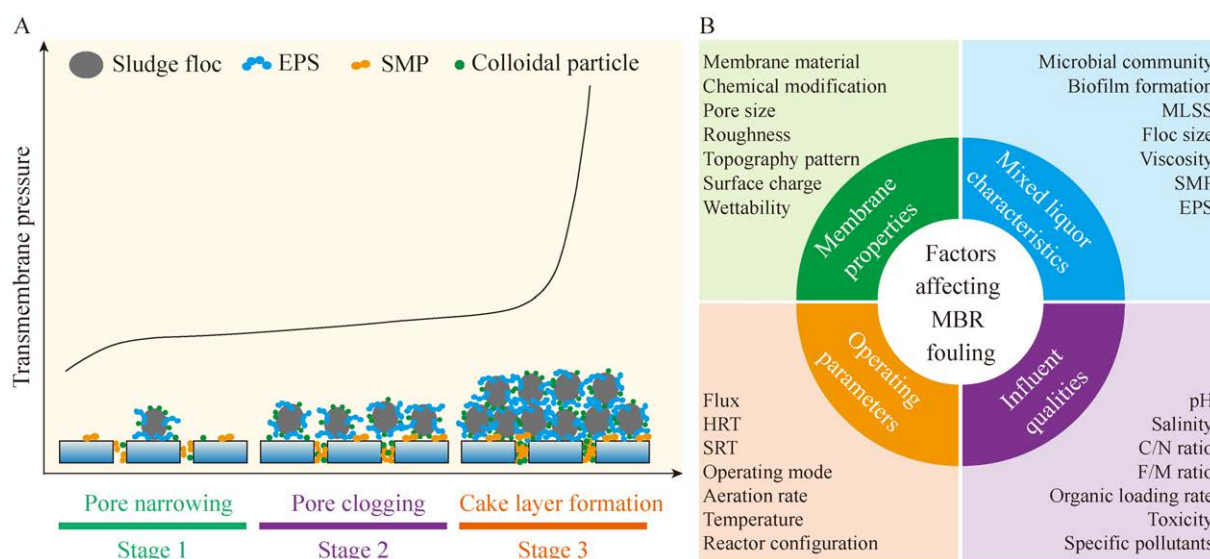


图 1 MBR 膜污染形成过程(A)与影响因素(B)示意图

Figure 1 Schematic diagram of the formation processes (A) and key influencing factors (B) of membrane fouling in MBRs.

Ca^{2+} 、 Mg^{2+} 、 Fe^{3+} 、 Al^{3+} 、 SO_4^{2-} 、 PO_4^{3-} 、 CO_3^{2-} 、 OH^- 等是膜污染中常见的无机盐离子^[26]。无机盐离子与有机物形成的复合物沉淀也是无机污染的重要来源^[27]。例如， Ca^{2+} 在较高浓度时主要是形成无机盐沉淀，而在较低浓度时主要作为阳离子架桥与有机物结合形成复合膜污染^[28-29]。利用酸、碱等化学试剂进行清洗是去除无机污染的最有效方法。

(2) 有机污染，指溶解性有机物或者胶体(如腐植酸、富里酸和微生物产生的蛋白、多糖等)在膜表面发生吸附和沉积。自然水体和污水中普遍存在溶解性有机物，根据其来源可以分为天然有机物、人工合成有机物和微生物代谢产生的 SMP^[30]。在 MBR 系统中，SMP 对膜污染的形成起着重要作用，其可以形成过滤阻力特别大的凝胶层(gel layer)；有研究认为 SMP 引起的有机污染占总体膜污染的 26%–52%^[31]。微生物合成并分泌到胞外的 EPS 是 SMP 的主要来源，SMP 中的主要成分与 EPS 相似，包括蛋白、多糖、核酸等物质，SMP、EPS 的含量和组分特征与膜污染情况密切相关^[32-33]。此外，由大分子有机物和少量微生物组成的生物高聚物簇(biopolymer clusters, BPC)也是膜污染的重要贡献者，特别是粒径为 1–8 μm 的 BPC

是导致严重膜污染的关键原因^[34]。

(3) 生物污染(biofouling)，主要指微生物附着在膜材料表面进行生长繁殖，并且通过分泌 EPS 将细胞有序连接、包裹，形成具有复杂三维结构的生物膜。生物污染被认为是最难去除的膜污染类型^[35-36]，因为微生物是 MBR 系统的重要组成部分，无时无刻不在与膜材料表面发生相互作用。如图 2 所示，膜材料表面生物膜的形成过程一般可以分为 5 个阶段，即细胞的初始黏附(initial attachment)、分泌 EPS 强化不可逆黏附(irreversible attachment)、微菌落形成(microcolony formation)、生物膜结构成熟及分化(maturation and differentiation)以及老化和细胞的逸散(aging and cell dispersal)^[37]。微生物在膜材料表面附着并形成生物膜是一个复杂的动态过程，涉及多种细胞和分子调控机制^[38]，同时也受到包括环境条件(如温度、pH、盐度、钙离子等)在内的多重因素的影响^[39-40]。

在含有高密度微生物的 MBR 系统中，膜材料表面的生物污染特征明显、对总污染的贡献显著，同时生物污染也常与有机污染、无机污染等耦合在一起形成复合膜污染。因此，如何去除或抑制生物污染长期以来是 MBR 膜污染控制研究领域的重点和难点^[41-42]。

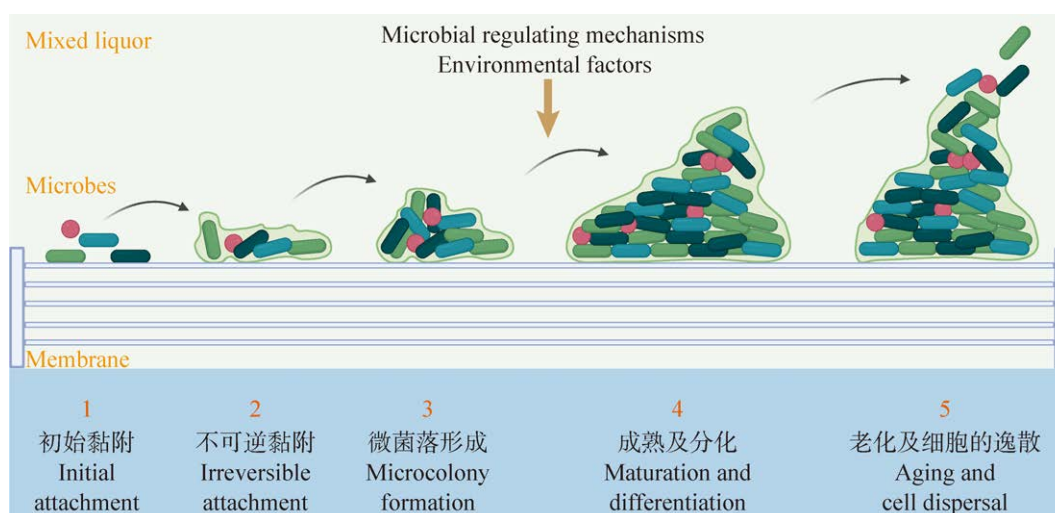


图 2 膜材料表面的生物膜形成过程示意图

Figure 2 Schematic diagram of biofilm formation on membrane surfaces.

2 基于群体感应效应的 MBR 膜污染控制原理

2.1 群体感应效应在膜污染形成中的作用

微生物在膜材料表面以生物膜形式附着生长并逐渐形成滤饼层是造成 MBR 膜污染的重要原因,而采用物理或化学控制措施并不能从根源上防止此过程的发生。因此,基于生物膜形成的微生物学机制,寻找可以从源头上阻断该过程的控制方法,才有可能实现长效、低成本、绿色可持续的 MBR 膜污染控制。

生物膜是细菌等微生物为了在复杂多变的环境条件下生存和繁殖,而发展出的一种具有诸多优势的群体性生活方式^[43]。相较于处于浮游状态的细菌,生物膜是一个细胞密集的小型生态系统,需要细胞之间的相互交流合作才能维持相应的群落结构和功能。研究普遍认为,作为细菌交流机制的 QS 在生物膜的形成过程中发挥了关键性的调控作用^[44-45]。当黏附于非生物材料表面的细菌达到一定数量,其向外合成分泌的化学信号分子(signaling molecules)密度也随之达到一定阈值,这些信号分子可被周围其他细菌细胞的受体蛋白识别和结合,进而启动下游与 EPS 合成等功能相关的基因转录和表达,最终促进生物膜三维结构的形成和功能分化^[46-47]。

QS 调控通路中最关键的化学物质基础就是由微生物细胞合成分泌的信号分子,也被称为自诱导物(autoinducer, AI)。目前已被研究识别的信号分子有多个类别:最常见的是由革兰氏阴性菌如铜绿假单胞菌(*Pseudomonas aeruginosa*)等合成分泌的 N-酰基高丝氨酸内酯(N-acyl-homoserine lactone, AHL)类信号分子,通常由 1 个高丝氨酸内酯环和碳原子数不同(4-18 个)的酰基侧链构成,也被称为 autoinducer-1 (AI-1),目前已在变形菌门(*Proteobacteria*)的 100 多个菌属的细菌中被检测

到^[48-49];革兰氏阳性菌合成的信号分子主要是寡肽类物质,被称为 autoinducer peptide (AIP)^[50];由呋喃酰硼酸二酯等硼酸-呋喃衍生物构成的 autoinducer-2 (AI-2)是在革兰氏阴性菌和阳性菌中都存在的一类信号分子,可用于跨种属的细菌交流^[51];此外,还存在一些较为特殊的信号分子,如在大肠埃希氏菌(*Escherichia coli*)中发现的含氮杂环类信号分子 autoinducer-3 (AI-3)^[52]、在 *P. aeruginosa* 中发现的以 2-庚基-3-羟基-4(1H)-喹诺酮为代表的喹诺酮信号分子(*Pseudomonas* quinolone signal, PQS)^[53]、在植物致病菌中常见的由顺式不饱和脂肪酸构成的扩散性信号因子(diffusible signal factor, DSF)类信号分子^[54]等。

目前,在实验室规模和实际规模的 MBR 系统内均能检测到多种信号分子的分布。例如,使用色谱-质谱联用(如液相色谱-三重四极杆质谱、液相色谱-傅里叶变换质谱等)和生物传感菌[主要为紫色色小杆菌(*Chromobacterium violaceum* CV026)和根癌农杆菌(*Agrobacterium tumefaciens* NTL4)]等方法,可检测到不同酰基侧链长度和 3 号位取代基的 AHL 类信号分子(C4-HSL, C6-HSL, C7-HSL, C8-HSL, C10-HSL, C12-HSL, C14-HSL, 3OC6-HSL, 3OC8-HSL, 3OC10-HSL, 3OC12-HSL, 3OC14-HSL)^[55-58]。不同 MBR 系统中主导的 AHL 类型存在差异,其浓度范围一般在 1-500 ng/L,并且膜材料表面生物膜中的 AHL 种类和含量高于悬浮污泥中的 AHL^[15,59]。此外,有研究使用基于哈维氏弧菌(*Vibrio harveyi*) BB170 作为生物传感菌的检测方法在 MBR 系统检测到 AI-2 类信号分子,并发现其含量在严重膜污染发生时显著升高^[60]。然而,很少有研究在 MBR 系统中直接检测到其他类型的信号分子,有研究利用宏基因组学分析手段,识别到 MBR 中与 AIP、DSF、PQS 等信号分子相关的物种和基因^[59,61]。这些研究结果表明,基于不同信号分子的 QS 调控机制在 MBR 膜污染形成过程中发挥了重要作用。

2.2 人工干预群体感应效应的途径

由于 QS 对生物膜形成至关重要,若存在某种生物机制能干扰 QS 系统使其无法发挥调控作用,则可以达到抑制生物膜形成的效果,进而实现对 MBR 膜污染的控制。QQ 就是这样一种通过对微生物细胞间的 QS 系统产生干扰和阻碍,抑制 QS 依赖性基因的转录和表达,从而消除 QS 具体调控作用的机制或策略^[14]。针对 QS 系统的调控通路,QQ 策略主要有 3 种实现形式^[13](图 3)。

(1) 抑制信号分子的产生,可以使 QS 系统失去激活相应调控通路的物质基础,从而实现 QQ 效果。例如, AHL 类信号分子主要有 3 类合成蛋白 HdtS、LuxI 和 LuxM,其中 LuxI 以 S-腺苷甲硫氨酸(S-adenosyl-L-methionine, SAM)和酰基载体蛋白(acylated acyl carrier protein, acyl-ACP)为前体物进行 AHL 合成^[62]。

SAM 和 acyl-ACP 结合到合成蛋白上之后, SAM 的氨基对 acyl-ACP 的 1 号位羰基碳进行亲核攻击而发生 N-酰化反应(N-acylation),随后 SAM 自身发生内酯化反应(lactonization),从而生成 AHL 产物^[63]。一些化合物(如西奈芬净、丁酰-S-腺苷甲硫氨酸、全酰基载体蛋白等)与上述前体物结构相似,可实现对 AHL 合成过程的干扰和抑制^[64-65]。然而, SAM 是甲基化反应中主要的甲基供体,直接参与脂肪代谢、氨基酸的转移再生、嘌呤与嘧啶的生物合成等多个过程; acyl-ACP 直接参与脂肪酸生物合成过程^[63]。若使用与 SAM、acyl-ACP 结构相似的化合物作为 QS 抑制剂,则会同时干扰细胞的多种基础代谢途径,从而影响微生物正常生长,因而这些物质不太适合在依赖微生物的 MBR 系统中使用。

(2) 灭活或降解信号分子,也可使 QS 系统

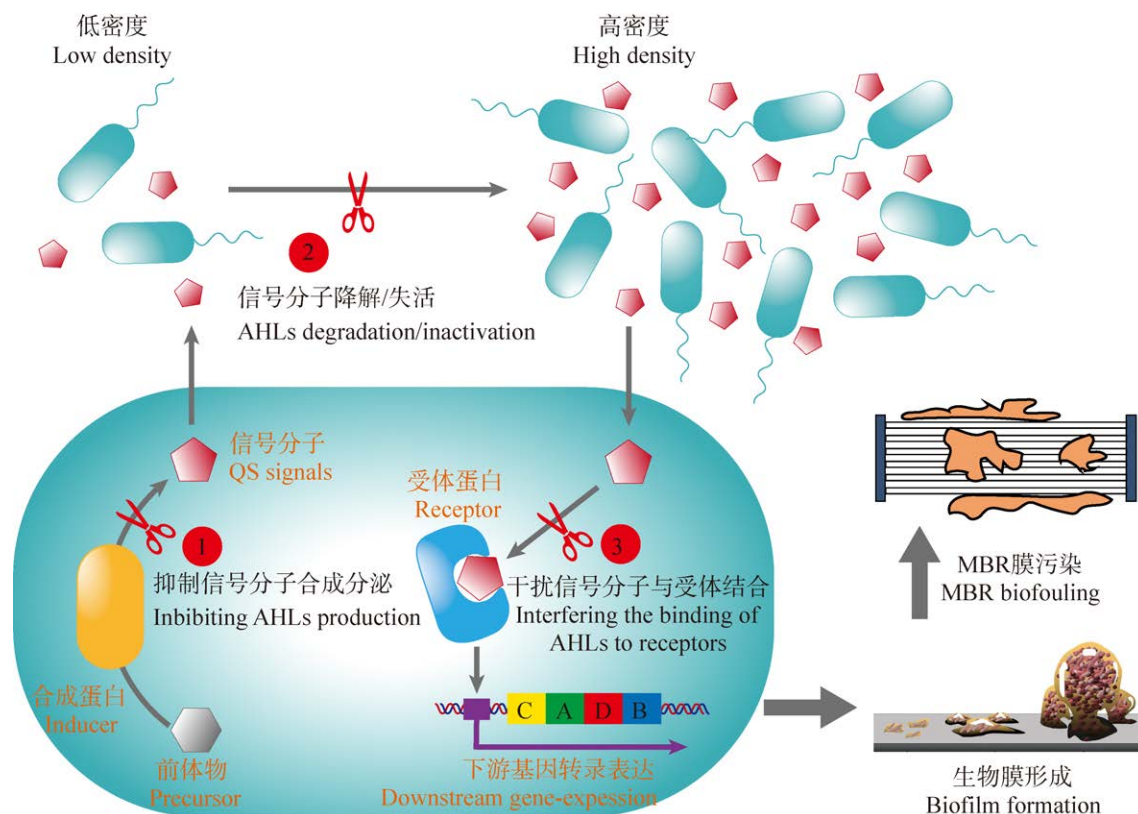


图 3 细菌群体感应效应途径和实施群体感应淬灭策略的 3 种方法

Figure 3 Bacterial quorum sensing pathways and the three ways to conduct quorum quenching strategies.

失去物质基础,被认为是干扰 QS 调控通路的最直接有效的方式。该过程通常在细菌细胞之外实现,因而可以最小化对细胞正常生长和代谢功能的影响。环境中存在的一些细菌可以合成分泌具有信号分子降解功能的酶(即 QQ 酶),这些 QQ 酶通过催化反应可使信号分子结构发生改变并失去活性,这类细菌也被称为 QQ 菌^[66-67]。QQ 菌和 QQ 酶来源于生物资源,具有可再生的特点,是目前广泛使用的 QQ 策略。

(3) 干扰信号分子与受体的结合,即利用一些与信号分子结构类似的化合物,使其竞争性地结合信号分子受体蛋白,显著降低信号分子与受体蛋白的结合效率,从而实现 QQ 效果。例如,呋喃酮(furanone)及其衍生物与 AHL 结构相似,可以与其竞争性地结合受体蛋白,从而干扰 QS 通路并抑制生物膜形成;呋喃酮在自然界中广泛存在,多种海洋和陆生植物如海洋红藻(*Delisia pulchra*)、草莓、咖啡等以及真菌如曲霉属(*Aspergillus*)等都可产生该类化合物^[68-69]。此外,双环溴化呋喃酮(brominated furanones)和 D-核糖(D-ribose)等是与 AI-2 类信号分子结构相似的化合物,可以竞争性地与 AI-2 受体蛋白结合,从而抑制 QS 系统及生物膜形成,并且不会引起明显的细胞毒性^[70-71]。这类化合物也被称为 QS 抑制剂,目前已在生物、医学、农业、环境等领域得到广泛研究和应用。

3 群体感应淬灭控制 MBR 膜污染的实现策略

3.1 群体感应淬灭活性物质的筛选与应用

3.1.1 群体感应淬灭化合物

在 MBR 系统中已得到应用的 QQ 化合物主要是与信号分子竞争性地结合受体蛋白的化合物。例如,与 AHL 类信号分子结构相似的呋喃酮及其衍生物,对细胞的毒性很小,很适用于 MBR 膜污染控制。有研究选用 2(5H)-呋喃酮作为 QQ 化合物去控制厌氧 MBR 膜污染,

添加浓度为 6 mg/L 时可使膜污染周期延长 100%,对系统处理效能没有影响且可增加甲烷产率;通过组学分析发现,2(5H)-呋喃酮除了竞争 AHL 的受体蛋白之外,还可以促进 QQ 酶的合成,从而增强 QQ 效果^[72]。在 MBR 系统中应用与 AI-2 类信号分子相似的化合物 D-核糖(100 $\mu\text{mol/L}$),可显著抑制 EPS 和 SMP 的产生,进而延缓膜污染过程^[73]。从香草中提取的香草醛(vanillin)是另一种常见的可干扰 QS 系统的化合物^[74]。在 MBR 系统中添加 160 mg/L (以 C 计)的香草醛,可实现对膜污染的有效抑制,其通过影响系统中的微生物群落结构进而改变了悬浮污泥的黏附特性^[75]。另外,将香草醛固定在膜材料表面,由于可直接作用于膜表面微生物且具有缓释效果,显著提升了其利用效率和持续作用时间,可获得比直接投加药剂更佳的膜污染控制效果^[76]。考虑到实际应用的需求,未来还需要不断优选价格低廉、来源广泛、绿色可再生、对活性污泥微生物正常功能影响小的高活性 QQ 化合物。

3.1.2 群体感应淬灭酶

QQ 酶可通过催化反应降解或改变信号分子结构,进而实现 QQ 效果。由于 QQ 酶主要来自微生物的合成分泌,也可通过生物工程生产,成本相对可控,对微生物生长代谢的影响很小,因此也适用于 MBR 膜污染控制。目前,研究中筛选和应用的 QQ 酶主要是针对 AHL 类信号分子的降解酶,根据反应原理可以分成三大类(图 4)^[67],即:(1) 内酯酶(lactonase),作用于 AHL 结构中的高丝氨酸内酯环,使其发生水解反应,相应的产物为 N-酰基高丝氨酸(N-acyl-homoserine, AHS);(2) 酰基转移酶(acylase),使 AHL 结构中连接高丝氨酸内酯环和酰基侧链的酰胺键断开,其转化产物为高丝氨酸内酯(homoserine lactone, HSL)和脂肪酸(fatty acid);(3) 氧化还原酶(oxidoreductase),通过催化氧化还原反应直接使 AHL 结构发生显著改变,从而失去相应的生物活性。研究也

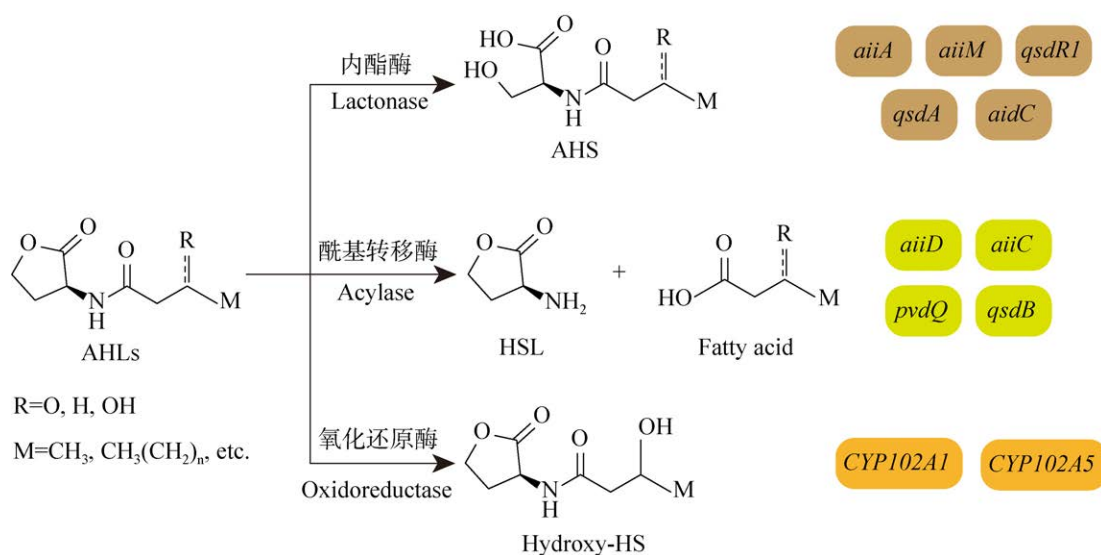


图 4 群体感应淬灭菌合成的 N-酰基高丝氨酸内酯降解酶及其催化反应途径和常见合成基因。AHLs: N-酰基高丝氨酸内酯; AHS: N-酰基高丝氨酸; HSL: 高丝氨酸内酯; Hydroxy-HS: 羟基-高丝氨酸。

Figure 4 N-acyl-homoserine lactone-degrading enzymes synthesized by quorum quenching bacteria and their catalytic reaction pathways and common synthetic genes. AHLs: N-acyl-homoserine lactones; AHS: N-acyl-homoserine; HSL: Homoserine lactone; Hydroxy-HS: Hydroxy-homoserine.

已经识别到很多 QQ 酶对应的合成基因(图 4): 内酯酶的合成基因有芽孢杆菌属(*Bacillus*)的 *aiiA* 基因^[77], 微杆菌属(*Microbacterium*)的 *aiiM* 基因^[78], 根瘤菌属(*Rhizobium*)的 *qsdR1* 基因^[79], 红球菌属(*Rhodococcus*)的 *qsdA* 基因^[80], 以及金黄杆菌属(*Chryseobacterium*)的 *aidC* 基因^[81]等; 酰基转移酶的合成基因有罗尔斯通氏菌属(*Ralstonia*)的 *aiiD* 基因^[82], 鱼腥藻属(*Anabaena*)的 *aiiC* 基因^[83], 假单胞菌属(*Pseudomonas*)的 *pvdQ* 基因^[84], 以及土壤细菌中的 *qsdB* 基因^[85]等; 对氧化还原酶的研究报道较少, 主要有在 *Bacillus* 发现的细胞色素 P450 单加氧酶 CYP102A1 和 CYP102A5^[86-87]等。上述 QQ 酶中, 酰基转移酶在膜污染控制中应用最多, 例如将酰基转移酶固定修饰在膜材料表面, 可实现对膜污染的延缓^[88-91]。酰基转移酶来源广泛, 多种细菌如争论贪噬菌(*Variovorax paradoxus*)、*Ralstonia* spp.、*P. aeruginosa* 等都可以合成, 其中从 *P. aeruginosa* 中分离得到的 PvdQ 酶的结构已被完整表征^[64,84]。酰基转移酶的规模化生产一

般从猪肾、曲霉属(*Aspergillus*)等生物材料中提取制备^[92], 市面上已有成熟产品。但 QQ 酶的实际应用也面临药剂成本较高、在复杂环境条件下易失活或无法长效维持活性等问题, 仍亟待解决。

3.1.3 群体感应淬灭菌

QQ 菌可以持续地合成 QQ 酶去降解细胞周围的信号分子, 从而阻断其他细菌的 QS 调控通路, 最终实现对 EPS 产生和生物膜形成的抑制。因此, 相较于使用 QQ 化合物和 QQ 酶, 采用 QQ 菌进行 MBR 膜污染控制具有绿色可持续、成本低、负面作用小的优势, 近来已成为研究热点。目前, 在 MBR 膜污染控制中得到应用的 QQ 菌株, 大部分是从活性污泥、土壤等环境介质中分离和纯化而来, 也有通过基因工程手段获得的重组 QQ 菌株。例如, 红球菌(*Rhodococcus* sp.) BH4、肠球菌(*Enterococcus* sp.) HEMM-1、芽孢杆菌(*Bacillus* sp.) SDC-U1 等可以合成内酯酶, 对多种 AHL 信号分子都有降解能力^[80,93-96]; 假单胞菌(*Pseudomonas*

sp.) 1A1、代尔夫特菌(*Delftia* sp.) JL5、重组大肠埃希氏菌(*E. coli*)-pET-PvdQ 等则可以合成酰基转移酶去降解 AHL 信号分子^[97-99]；不动杆菌(*Acinetobacter* sp.) DKY-1 可以通过合成分泌一种非酶类的小分子活性物质实现对 AI-2 类信号分子的降解，泛菌属(*Pantoea* sp.) PL-1 也具有 AI-2 降解功能^[100-101]。由此可见，QQ 菌在微生物生态体系中是广泛分布的；更重要的是，相较于具有 QS 功能的细菌，微生物群落中的 QQ 菌及其展现的 QQ 功能活性往往更加持久^[102]，这也凸显了 QQ 菌的应用潜力。表 1 总结了目前研究中报道的常见用于 MBR 膜污染控制的 QQ 菌株及其基本特征。

3.2 群体感应淬灭固定化技术

在获取高效的 QQ 活性物质之后，还需要选用合适的在 MBR 系统中应用的具体形式。相对于直接投加，将 QQ 活性物质固定于特殊载体之后再应用，一般可实现更稳定可靠的膜污染控制效果。采用固定化技术的原因在于：减少 QQ 活性物质的流失；保护 QQ 活性物质不受系统中其他不利因素的干扰；载体可为

QQ 菌提供良好的溶解氧、营养和基质等的传输效果；载体具有良好的物理、化学及生物稳定性；增加与膜材料表面的接触机会等。

3.2.1 基于海藻酸钠的固定化

海藻酸钠(sodium alginate, SA)与钙离子通过交联反应形成的具有三维网络结构的凝胶状复合物是一种常用的固定化载体。将扩培后的 QQ 菌细胞与 SA 溶液混合，再加入到氯化钙溶液中，可制备成包埋 QQ 菌的凝胶材料，这种载体具有一定的机械性能和稳定性，且可维持 QQ 菌的活性。例如，将 QQ 菌株 *Rhodococcus* sp. BH4 固定于 SA 形成 QQ 小球，可以使 MBR 达到预设 TMP 阈值所用的时间(即膜污染周期)延长 10 倍^[113]；相应地，系统中的 AHL 浓度和 EPS 产生量都显著降低，QQ 小球通过物理作用(即机械冲刷膜材料表面的滤饼层)和生物作用(即降解 AHL 进而阻断 QS)的双重机制，实现了对膜污染的有效延缓^[114]。

利用 SA 作为固定化载体，研究不断开发新型的 QQ 菌固定化形式。例如，与 QQ 小球相比，具有细长结构的 QQ 圆柱因其更好的

表 1 常见用于 MBR 膜污染控制的群体感应淬灭菌

Table 1 Quorum quenching bacteria used for MBR fouling control

群体感应淬灭菌 Quorum quenching bacteria	菌株特征 Strain characteristic	来源 Source	目标信号分子 Target signal molecule	QQ 酶及位置 QQ enzyme and its location	文献 Reference
<i>Rhodococcus</i> sp. BH4	Gram positive	Activated sludge from a real MBR, Korea	C6-HSL, C8-HSL, C10-HSL, C12-HSL, 3OC6-HSL, 3OC8-HSL, 3OC10-HSL, 3OC12-HSL	Lactonase, intracellular	[80,93]
<i>Pseudomonas</i> sp. 1A1	Gram negative	Activated sludge from a lab-scale MBR, Korea	C6-HSL, C8-HSL, C10-HSL, C12-HSL, 3OC12-HSL	Acylase, extracellular	[97]
<i>Bacillus methylophilus</i> WY	Gram positive	Activated sludge from a real sewage treatment plant, China	C8-HSL, C10-HSL, C12-HSL, C14-HSL, 3OC6-HSL, 3OC8-HSL, 3OC12-HSL	Lactonase	[103]
<i>Enterococcus</i> sp. HEMM-1	Gram positive	Activated sludge from a real MBR, Korea	C4-HSL, C6-HSL, C8-HSL, 3OC6-HSL, 3OC12-HSL	Lactonase, extracellular	[94]

(待续)

(续表 1)

群体感应淬灭菌 Quorum quenching bacteria	菌株特征 Strain characteristic	来源 Source	目标信号分子 Target signal molecule	QQ 酶及位置 QQ enzyme and its location	文献 Reference
<i>Lactobacillus</i> sp. SBR04MA	Gram positive	Activated sludge from a real sewage treatment plant, Greek	C6-HSL	Enzyme unknown	[104]
<i>Microbacterium</i> sp. HSY-2	Gram positive, facultative anaerobic	Activated sludge from a real sewage treatment plant, Korea	C6-HSL	Enzyme unknown, intracellular	[105-106]
<i>Bacillus</i> sp. SDC-U1	Gram positive, facultative anaerobic	Activated sludge from a real MBR treating industrial wastewater, Korea	C6-HSL, C8-HSL, C10-HSL, C12-HSL, 3OC6-HSL, 3OC8-HSL, 3OC10-HSL, 3OC12-HSL	Lactonase, intracellular	[95-96]
<i>Brucella</i> sp. ZJ1	Gram negative	Activated sludge, China	C6-HSL	Enzyme unknown	[107]
<i>Delftia</i> sp. JL5	Gram negative	Activated sludge from a real MBR, China	C8-HSL	Acylase, intracellular	[98]
<i>Stentrophomonas</i> sp. Y6	Gram negative	Activated sludge and soil, China	C6-HSL, C8-HSL	Enzyme unknown, extracellular	[108]
<i>Listeria grayi</i> HEMM-2	Gram positive	Activated sludge from a real MBR, Korea	C4-HSL, C6-HSL, C8-HSL, 3OC6-HSL, 3OC12-HSL	Enzyme unknown, extracellular	[109]
<i>Lysinibacillus</i> sp. A4	Gram positive	Soil, China	C6-HSL, C8-HSL	Lactonase AilY	[110]
<i>Bacillus</i> <i>thuringiensis</i> LZX01	Gram positive	Activated sludge from a real MBR, China	C8-HSL	Lactonase, intracellular	[111]
<i>Escherichia</i> <i>coli</i> -pET-PvdQ	Gram negative	Recombinant bacteria	C4-HSL, C8-HSL, C12-HSL, 3OC12-HSL	Acylase PvdQ, extracellular	[99]
<i>Pseudomonas</i> <i>putida</i> KT2440-pBBR-aiiO	Gram negative	Recombinant bacteria	C6-HSL, C8-HSL, C12-HSL, 3OC6-HSL	Acylase AiiO	[112]
<i>Acinetobacter</i> sp. DKY-1	Gram negative	Activated sludge from a real MBR, Korea	The precursor molecule for the synthesis of AI-2: 4,5-dihydroxy-2,3-penta nedione (DPD)	A hydrophilic bioactive substance (non-enzyme) with a molecular weight of less than 400 Da, extracellular	[100]
<i>Pantoea</i> sp. PL-1	Gram negative, facultative anaerobic	Activated sludge from a real sewage treatment plant, Korea	DPD	A small molecular weight hydrophilic bioactive substance, intracellular and extracellular	[101]

QQ 活性和物理冲刷效应,对 MBR 膜污染具有更好的控制效果;这是因为 QQ 酶对信号分子的降解往往发生在载体表面而非内部,因此,在固定相同数量 QQ 菌的前提下,具有更高比表面积载体将具有更高的 QQ 效率^[115]。此外,QQ 空心圆柱^[116]、QQ 薄片^[117]等形式的固定化载体因具有特殊的三维结构,也表现出比 QQ 小球更好的 QQ 活性和更强的膜污染抑制能力。

3.2.2 基于复合材料和多层结构的固定化

通过引入多种复合材料和设计特殊的多层结构,可提升 QQ 固定化载体的综合性能和实用价值。SA 凝胶材料在 MBR 运行过程中随着复杂的水力条件和机械冲刷作用,仍易于磨损甚至解体。为此,在 SA 固定化过程中引入其他高分子材料如聚乙烯醇(polyvinyl alcohol, PVA)、聚砜(polysulfone, PSF)等形成 SA-PVA、SA-PSF 复合材料^[118-119],或者引入粉末活性炭(powdered activated carbon, PAC)形成 SA-PAC 复合材料^[120],可进一步提升固定化载体材料的机械性能和稳定性。在 SA 凝胶材料中引入具有生物刺激作用的物质,可增强被包埋 QQ 菌的活性。例如,有研究将与 AHL 结构类似的 γ -己内酯(γ -caprolactone, GCL)作为生物刺激物包埋在 SA-PVA 小球的中心,并使 QQ 菌分布在小球的外层,内部核心缓释的 GCL 可以持续强化外层 QQ 菌的活性,从而保证其长期发挥 QQ 功能和膜污染控制效果^[121]。

核-壳(core-shell)双层结构的设计和制备也可以显著改善 QQ 固定化载体材料的性能。例如,通过静电纺丝技术(electrospinning)制备一层聚偏二氟乙烯(polyvinylidene fluoride, PVDF)外壳,再将含有 QQ 菌的 SA-PVA 小球包裹在外壳的内部,形成具有良好机械强度的 QQ 固定化核-壳结构,可大幅延长 QQ 活性的维持时间并降低 QQ 菌的使用剂量^[122]。将含有 QQ 菌的 SA-PVA 薄片包裹在通过 3D 打印技术制备的聚乳酸纤维多孔外壳中,也可形成具有核-壳双层结构的 QQ 球体,这种固定化形式可显著提

升抗膜污染性能和载体稳定性,并可节省 50%左右的能源消耗,QQ 活性可维持 160 d 上^[123]。还有研究先用壳聚糖覆盖在包埋 QQ 菌的 SA 小球表面,再用 SA/聚丙烯酰胺制备一层具有半互穿网络结构(semi-interpenetrating network, SIPN)的坚硬外壳,最后将 SA 小球包裹在外壳内部形成三维 QQ 固定化核-壳结构,也获得了良好的膜污染控制效果,并显著提升了固定化载体材料的机械强度和使用寿命^[124]。

多孔二氧化硅的比表面积大,具有优异的吸附性能,也常被用作固定化载体材料。有研究将 QQ 菌吸附于二氧化硅表面,再将其包埋于 SA-PVA 材料之中,形成 QQ 固定化核-壳结构,可大幅提升载体材料的抗压强度,并可获得更好的膜污染控制效果^[125];另有研究利用吸附 QQ 菌的二氧化硅粉末与聚合高分子电解质制备出 QQ 固定化复合载体材料,显著延缓了厌氧 MBR 的膜污染过程,在使用 40 d 后仍能维持 90%以上的 QQ 活性,表现出比 SA 凝胶材料更好的耐用效果^[126]。

3.2.3 基于半透膜的固定化

QQ 菌束缚在封闭的半透膜材料中制成 QQ 膜管束或 QQ 膜包,也是一种有效的固定化方法。所选膜材料的孔径小于细菌的尺寸,可以保证 QQ 菌只能在膜材料内部生长和代谢而不会流失,营养物质、代谢产物以及信号分子等物质则可以自由地从膜孔中进出^[93]。例如,将 QQ 菌 BH4 固定于 PVDF 中空纤维膜管中,可使 MBR 膜污染周期延长 69.6%^[127];将 BH4 固定于“饺子”形状的 PVDF 膜包中,也可使膜污染周期延长 26.9%^[128]。还有研究设计出一种板框式的固定化结构,该结构的两面为 PVDF 微孔滤膜,边框为聚碳酸酯材料,将 QQ 菌束缚在这种板框结构中,可以保证其与外界进行正常的物质交换;在 MBR 运行过程中,将 QQ 板框与机械搅拌装置相连,可使 TMP 增长速率下降 65%,QQ 板框通过水力扰动和 QQ 功能的双重作用实现了膜污染延缓,并且能在长期运

行过程中保持 QQ 活性^[129]。

3.2.4 膜材料表面负载修饰

将 QQ 活性物质(通常是 QQ 酶和 QQ 化合物)负载于膜材料表面形成功能性涂层,也是研究中常用的 QQ 固定化策略。例如,酰基转移酶常被用来固定在膜材料表面进行 QQ 功能修饰。有研究先将酰基转移酶与壳聚糖混合形成聚合体,再通过高压将此聚合体负载于聚酰胺纳滤膜上,最后使用戊二醛作为交联剂强化负载效果;实验发现这种经过修饰的纳滤膜可较长时间维持 QQ 酶活性,能有效抑制 EPS 产生和生物膜形成,并显著延缓膜污染过程^[89]。将酰基转移酶通过吸附、沉积、交联等过程先结合在碳纳米管上,再将此碳纳米管负载于表面涂覆一层聚多巴胺的 PVDF 膜材料上,聚多巴胺涂层依靠邻苯二酚、醌和胺等基团可提供丰富的结合位点;以这种方式修饰的膜材料可显著抑制生物膜形成并增强透水性,在连续流膜过滤实验中可使膜污染周期延长 60%^[90]。相似地,在预先涂覆聚多巴胺的聚酰胺膜材料上,通过戊二醛共价结合作用分别负载酰基转移酶和另一种针对 PQS 调控通路的 QQ 化合物邻氨基苯甲酸甲酯,由此制备的 2 种 QQ 修饰膜材料均能显著抑制 EPS 产生和控制膜污染^[91]。其他的 QQ 化合物如香草醛、肉桂醛等也被负载于膜材料表面,进而实现膜污染控制效果^[76,130]。

表 2 总结了上述研究中所应用的 4 类 QQ 固定化策略。从表 2 可以看出,利用特定固定化形式的 QQ 活性物质去控制 MBR 膜污染是一种有效策略,并且固定化 QQ 菌的应用更广泛。随着大量 QQ 菌的分离纯化和新型固定化形式的开发,QQ 策略应用覆盖的废水范围从模拟市政污水逐渐拓展到实际市政污水^[119]以及含不同特征污染物的工业废水^[96,120]等,覆盖的 MBR 工艺类型也从好氧 MBR 拓展到厌氧 MBR^[118,131-132],展现了极具前景的应用潜力。对于 QQ 固定化载体材料的开发和优化,未来的研究重点仍是不断提升材料的机械稳定性、

比表面积、传质性能以及 QQ 活性维持时间,增强其对各种不利因素的耐受性,并在功能和成本之间达成最优平衡。

4 群体感应淬灭策略对 MBR 微生物生态的影响

QQ 策略的应用一般不会显著影响微生物的正常生长和基础代谢过程,对各类污染物去除效能的影响也很小,因而不会影响 MBR 系统的正常运行。但已有研究表明,废水处理反应器中 QS 条件的改变会显著影响微生物种间相互作用模式、群落构建机制以及群落动力学过程,最终塑造微生物群落的结构和功能性状^[133]。相应地,QQ 策略的引入也会直接干扰 MBR 系统内原有微生物生态体系的 QS-QQ 动态平衡条件,因此,需要关注该策略对 MBR 系统微生物群落结构和功能的影响。

4.1 基于 *Rhodococcus* sp. BH4 的 QQ 策略对 MBR 微生物群落的影响

Rhodococcus sp. BH4 是目前研究和应用最多的一株 QQ 菌,早期研究专注于该菌的膜污染控制效果和应用优化,近来随着分子生物学技术和微生物生态学的快速发展,研究也逐渐关注其对 MBR 微生物群落的影响。有研究发现菌株 BH4 (固定于 SA-PVA 小球)显著改变了 MBR 系统内微生物群落的组成结构和演替速率;该 QQ 策略降低了硫发菌属(*Thiothrix*)的丰度,此类丝状菌可通过 QS 调控 EPS 合成分泌,具有较强的生物膜形成能力,被认为是膜污染的重要贡献者^[134]。向 MBR 系统中直接接种未固定化的菌株 BH4,也可降低悬浮污泥微生物群落中优势物种 *Thiothrix* 的丰度,同时这种 QQ 策略提高了系统内微生物群落的多样性和均匀度^[135]。

然而,也有研究得出不一致的结论:在联合采用 QQ 策略和膜组件振动策略的 MBR 系统中,菌株 BH4 (固定于 SA-PVA 薄片,接种量 200 mg/L)虽然也可降低 *Thiothrix* 的丰度,但其

表 2 MBR 膜污染控制常用的群体感应淬灭固定化策略

Table 2 Quorum quenching immobilization strategies for MBR fouling control

固定化策略 Immobilization strategy	固定化形式 Immobilization media design	载体特征 Characteristic of QQ media	膜污染控制效果 Fouling control performance	QQ 活性维持 时间 Duration of QQ activity	文献 Reference
基于海藻酸钠 的固定化 Immobilization based on sodium alginate	QQ beads	Sodium alginate (SA) gel beads, with defined mechanical properties and stability, subjected to the dual function of QQ activity and mechanical scouring	Compared to the MBR without QQ application, the fouling cycle is extended by 7 to 10 times	After 30 d, QQ activity increases by 3%	[113-114]
	QQ cylinders	Cylinders with elongated structures, offering a larger specific surface area, enhanced mechanical scouring, and stronger QQ activity	Compared to the MBR using QQ beads, the fouling cycle is extended by 60%	≥20 d	[115]
	QQ hollow cylinders	Hollow cylindrical structure, offering a larger specific surface area and enhanced mass transfer capability	Compared to the MBR using QQ beads, the fouling cycle is extended by 130%	≥40 d	[116]
	QQ sheets	Square-shaped sheet structure provides better contact and mechanical scouring effect on the inner membrane fibers of bundled hollow fiber membrane modules	Compared to the MBR using QQ beads, the fouling cycle is extended by 80%	≥24 d	[117]
基于复合材料和多层结构的 固定化 Immobilization based on composite materials and multilayer structures	SA-PVA beads	Incorporating the polymer material polyvinyl alcohol (PVA) into SA gel beads to enhance mechanical properties and stability	Compared to the MBR without QQ application, the fouling cycle is extended by 5 times	Both QQ activity and mechanical strength can be maintained for over 100 d	[119]
	SA-PSF beads	Encapsulating SA gel beads with a layer of polysulfone (PSF) to enhance mechanical properties and stability	Compared to the anaerobic MBR without QQ application, the fouling cycle is extended by 7.5 times	≥45 d	[118]
	SA-PAC beads	Incorporating powdered activated carbon (PAC) into SA gel beads to enhance mechanical properties and stability	Compared to the MBR without QQ application, the fouling cycle is extended by 4.5 times	≥45 d	[120]

(待续)

(续表 2)

固定化策略 Immobilization strategy	固定化形式 Immobilization media design	载体特征 Characteristic of QQ media	膜污染控制效果 Fouling control performance	QQ 活性维 持时间 Duration of QQ activity	文献 Reference
	Bio-stimulated core-shell QQ beads	Incorporating gamma caprolactone (GCL, a structural analog of AHLs) in the core of SA gel beads as a bio-stimulant, with QQ bacteria distributed in the outer layer to enhance QQ activity	Compared to the MBR without QQ application, the fouling cycle is extended by 46.7%	≥39 d	[121]
	Electrospun fiber coated hydrogel QQ beads (QQ-ECHB)	Encapsulating a certain number of SA-PVA beads containing QQ bacteria within a PVDF shell to form a three-dimensional core-shell structure, enhancing mechanical properties and stability	Compared to the MBR without QQ application, the fouling cycle is extended by 4 times	After 16 d, 95% of QQ activity is maintained	[122]
	Mobile porous hard-shell QQ balls	Encapsulating a certain number of SA-PVA sheets containing QQ bacteria within a polylactic acid (PLA) fiber shell to form a three-dimensional core-shell structure	Compared to the MBR using QQ sheets, the fouling cycle is extended by 36%	≥160 d	[123]
	Semi-interpenetrating network hydrogels-based QQ microcapsules	Encapsulating a certain number of SA-chitosan beads containing QQ bacteria within an SA-polyacrylamide shell to form a three-dimensional core-shell structure	Compared to the MBR without QQ application, the fouling cycle is extended by 2.3 to 2.8 times	After 100 d, 79% of QQ activity is maintained	[124]
	SA-Silica beads	Adsorbing QQ bacteria onto the surface of silica material, then embedding them into SA gel beads to form a core-shell structure	Compared to the MBR without QQ application, the fouling cycle is extended by 3 times	After 30 d, more than 80% of QQ activity is maintained	[125]
基于半透膜的 固定化 Immobilization based on semi-permeable membrane materials	QQ vessels	Encapsulating QQ bacteria within PVDF hollow fiber membranes, sealing both ends to form membrane vessels	Compared to the MBR without QQ application, the fouling cycle is significantly extended	≥80 d	[93]

(待续)

(续表 2)

固定化策略 Immobilization strategy	固定化形式 Immobilization media design	载体特征 Characteristics of QQ media	膜污染控制效果 Fouling control performance	QQ 活性维持时间 Duration of QQ activity	文献 Reference
膜材料表面负载修饰 Modification of membrane materials	QQ bags	Encapsulating QQ bacteria within PVDF membrane sheets, sealing the edges to form a “dumpling”-shaped membrane bag	Compared to the MBR without QQ application, the fouling cycle is extended by 26.9%	≥14 d	[128]
	QQ rotary microbial carrier frame	Encapsulating QQ bacteria within PVDF membrane sheets, sealing the edges with a polycarbonate frame, and connecting to a stirring device to form a rotary frame structure	Compared to the MBR without QQ application, the fouling cycle is extended by 65%	≥30 d	[129]
	QQ enzyme-immobilized membrane	Immobilizing acylases on carbon nanotubes first, then loading them onto PVDF membrane material	Compared to the pristine membrane, the fouling cycle is extended by 60%	After 200 d, 66% of QQ activity is maintained	[90]
	QQ compound-immobilized membrane	Immobilizing methyl anthranilate onto polyamide membrane material through covalent binding and crosslinking	Compared to the pristine membrane, the fouling cycle is extended by 18% to 22%	≥4 d	[91]

对整体微生物群落结构的影响不明显^[136]。菌株 BH4 (固定于 PVDF 膜包)则显著降低了 MBR 悬浮污泥和滤饼层中微生物群落的多样性;系统中本身存在的具有 QQ 功能的细菌如噬纤维菌属(*Cytophaga*)、红细菌属(*Rhodobacter*)、黄杆菌属(*Flavobacterium*)、金黄杆菌属(*Chryseobacterium*)等的丰度明显下降,这可能是由于外源接种菌株 BH4 的竞争作用所导致;而系统中具有 QS 功能的细菌则表现出不同的变化趋势,例如红环菌科(*Rhodocyclaceae*)的丰度受到抑制,而丛毛单胞菌科(*Comamonadaceae*)受到促进,这可能是由于这些细菌所依赖的 QS 信号分子存在差异^[128]。

有研究发现,QQ 策略在与其他因素耦合时才会对 MBR 微生物群落产生显著影响。例

如,菌株 BH4 (固定于 SA-PVA 小球)在 MBR 系统采用短 SRT 时对微生物群落没有明显影响;但采用长 SRT 时,其显著提升了黄科夫勒氏菌(*Kofteria flava*)的丰度,该种细菌可高效降解生物大分子(如纤维素)并可分泌具有抗菌能力的代谢产物,而作为生物膜形成菌的艾氏硫发菌(*Thiothrix eikelboomii*)的丰度则受到明显抑制,最终实现了较好的膜污染控制效果;此外,这种 QQ 策略还显著提高了系统内微生物群落的多样性^[137]。

基于微生物生态学分析工具和模型,QQ 策略被证明可以改变 MBR 系统中微生物群落的互作模式和构建机制。有研究利用不同固定化形式(SA-PVA 薄片、PVDF 膜管束)和不同接种剂量(0–135 mg/L)的菌株 BH4 控制膜污染,发

现 QQ 策略对 MBR 系统微生物群落的多样性及组成结构没有明显影响,而其他因素(如进水类型和系统运行时间)的影响则很显著;但基于物种关联网络分析的结果显示,QQ 策略促进了滤饼层微生物群落中的种间相互作用(网络中的连接数量显著增加)^[138]。菌株 BH4 (固定于 PVDF 膜管束)对 MBR 系统内微生物群落的多样性和组成结构没有明显影响,但降低了球衣菌属(*Sphaerotilus*)、紫色杆菌属(*Janthinobacterium*)、塔希杆菌属(*Tahibacter*)、新衣原体属(*Neochlamydia*)、食酸菌属(*Acidovorax*)以及不动杆菌属(*Acinetobacter*)等与生物膜形成、EPS 分泌、细胞聚集等相关的菌属丰度;基于中性模型分析的结果显示,无论是否采用 QQ 策略,悬浮污泥和滤饼层中的微生物群落构建都是确定性过程(deterministic processes)主导的,但 QQ 策略会使滤饼层中的微生物物种扩散程度升高^[127]。

4.2 其他 QQ 策略对 MBR 微生物群落的影响

除了菌株 BH4,利用其他 QQ 菌的策略也对 MBR 微生物群落产生不同程度的影响。利用 QQ 菌 *Delftia* sp. JL5 (固定于 SA-PVA 小球)控制 MBR 膜污染,对悬浮污泥中的微生物群落影响较小,但显著改变了滤饼层中的微生物群落,特别是大幅提升了硝化螺菌门(*Nitrospirota*)在滤饼层中的相对丰度;该门类中的硝化螺菌属(*Nitrospira*)是一种生长速度缓慢的完全氨氧化菌,因此 QQ 策略可能有利于促进生长缓慢型物种在滤饼层中的定殖和富集^[98]。QQ 菌布鲁氏菌(*Brucella* sp.) ZJ1 (固定于 SA-PVA 小球)则显著抑制了 MBR 悬浮污泥微生物群落中的生物膜形成菌 *Thiothrix*,从而使膜污染得到缓解^[107]。将多株 QQ 菌[阴沟肠杆菌(*Enterobacter cloacae*) QQ13、微杆菌(*Microbacterium* sp.) QQ1 和 *Pseudomonas* sp. QQ3 等]配制成混合菌群(固定于 SA-PAC 小球),也可以显著改变 MBR 系统内悬浮污泥和滤饼层微生物群落的结构^[139]。此外,将基因工程重组 QQ 菌恶臭假单

胞菌(*P. putida*) KT2440-pBBR-aiiO 直接接种到活性污泥体系中,可显著抑制具有 QS 功能的土著细菌,并减弱微生物群落中的物种相互作用^[112]。

随着 QQ 策略拓展应用到厌氧 MBR 中,研究也发现其可以驱动厌氧微生物群落结构的演变。在厌氧 MBR 中应用 QQ 菌 *Microbacterium* spp. (固定于 SA-PSF 小球),可显著改变悬浮污泥和滤饼层中的微生物群落结构,*Nitrospira*、毛球菌属(*Trichococcus*)、厌氧绳菌科(*Anaerolineaceae*)等物种的丰度降低;该 QQ 策略也显著降低了悬浮污泥和滤饼层微生物群落的多样性,其可能原因是物种相互作用受到影响^[118]。同样地,QQ 混合菌群(固定于 SA-silica 小球和 SA-PVDF 膜管束)可显著改变厌氧 MBR 中与生物膜形成相关的微生物群落结构,从而延缓膜污染进程;但在 QQ 策略的影响下,具有稳定信号传导能力的物种会逐渐占据优势,这可能是膜污染无法彻底消除的原因^[132]。另有研究发现固定于 SA-PVA 小球的 QQ 混合菌群对厌氧 MBR 中的悬浮污泥微生物群落影响较小,但可显著降低膜材料表面初始生物膜中关键先锋菌属的丰度^[140]。

综上所述,QQ 策略对 MBR 微生物群落的影响是复杂的。首先,QQ 策略可显著降低一些与膜污染形成相关的微生物物种丰度,但其具体机制尚未明晰。其次,QQ 策略对不同 MBR 系统中的微生物群落结构和多样性的影响有很大差异,对悬浮污泥和滤饼层微生物群落的影响也不一致。此外,QQ 策略对 MBR 微生物群落中物种相互作用促进和减弱的效果也都存在。这些复杂的研究结论表明 QS/QQ 在塑造微生物群落中的作用是异质的,这可能与 QS 调控机制本身的多样性有关。一方面,QS 所依赖的信号分子种类很多,不同物种合成并利用不同的信号分子,而 QQ 策略对不同信号分子的作用也不相同。另一方面,QS 所调控的下游基因转录和表达非常多样,对微生物的

多种生理代谢行为和相互作用都有不同影响。因此,未来在实际应用 QQ 策略时,需要结合具体 MBR 系统的特异性参数,精准识别系统中的 QS 调控通路,进而揭示 QQ 对关键代谢行为的影响,解析微生物互作模式和群落构建机制,为塑造具有低膜污染潜势的 MBR 微生物群落提供可靠的微生物生态学依据和有效的人工干预方案。

5 结论与展望

膜污染是 MBR 工艺发展和应用过程中始终存在、亟待克服的关键问题。MBR 系统中的膜污染形成机制复杂,影响因素众多,其中主要由微生物活动导致的生物污染贡献巨大。QQ 策略通过阻断或干扰微生物的 QS 调控通路,可以有效抑制生物膜形成、胞外物质分泌等微生物活动,从而实现对膜污染的控制。近十几年来,研究通过分离筛选一系列 QQ 菌、QQ 酶和 QQ 化合物,设计和开发不同形式的固定化应用策略,在不同污废水和工艺条件的 MBR 试验系统中取得了显著的膜污染控制效果,展现了极具优势和潜力的应用前景。

然而,目前基于 QS 和 QQ 的 MBR 膜污染控制研究,还存在一些普遍的问题:(1) 在实际 MBR 工艺系统面临的复杂条件(如低温、高盐、高负荷、有毒有害污染物胁迫等)下, QS 对膜污染发生发展的具体贡献和作用机制尚未得到明确解析,导致在应用 QQ 策略时不够精准;(2) QQ 策略对 MBR 微生物群落结构和功能的长期影响及其分子机制尚未明晰,并且已有研究未形成一致结论,导致难以精准调控和维持 MBR 系统的长期稳定高效运行;(3) 研究分离和应用的 QQ 菌主要是针对 AHL 和 AI-2 这两类信号分子的降解菌,而 QS 调控机制所依赖的信号分子种类非常丰富,对其他类型信号分子的忽略可能会导致 QQ 策略的效果不佳;(4) 研究开发的各类固定化载体材料成本仍较高,在污染物复杂、水质条件多变的实际废水处理系统

中其综合性能也较难达到实验室模拟水平,距离 QQ 策略规模化应用仍存在一定差距。

针对上述问题,未来仍需要在以下几个方面开展更深入的工作:(1) 通过高分辨质谱和分子生物学等手段,全面识别 QS 在不同条件膜污染形成过程中的作用机制,为 QQ 策略的精准应用提供理论指导;(2) 借助宏基因组、宏转录组、蛋白组、代谢组等多组学技术手段,深入解析 QQ 策略对 MBR 微生物种间互作模式、群落构建机制、关键物质代谢功能通路等的影响,保证 MBR 系统的稳定高效运行;(3) 探索更多针对不同类型 QS 信号分子的 QQ 菌、QQ 酶等,不断丰富和优化 QQ 资源库,利用生物工程、合成生物学等手段制备低成本、可大规模使用的 QQ 活性物质;(4) 研发运行成本更低、QQ 活性维持时间更长的应用策略和固定化材料,充分考虑实际应用场景中的各种不利因素对材料本身性质和 QQ 活性的影响,必要时可将 QQ 策略与其他膜污染控制措施有机结合形成 QQ-物化耦合策略,以提升其适用性;(5) 对于研究提出的具体 QQ 策略,应采用技术经济分析和生命周期评价等方法进行全面核算和科学评估,为促进其规模化应用提供可行性依据。

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REFERENCES

- [1] HUANG LY, LEE DJ. Membrane bioreactor: a mini review on recent R&D works[J]. *Bioresour Technol*, 2015, 194: 383-388.
- [2] JUDD SJ. The status of industrial and municipal effluent treatment with membrane bioreactor

- technology[J]. Chemical Engineering Journal, 2016, 305: 37-45.
- [3] YAMAMOTO K, HIASA M, MAHMOOD T, MATSUO T. Direct solid-liquid separation using hollow fiber membrane in an activated sludge aeration tank[J]. Water Pollution Research and Control Brighton, 1988, 21: 43-54.
- [4] MENG FG, ZHANG SQ, OH Y, ZHOU ZB, SHIN HS, CHAE SR. Fouling in membrane bioreactors: an updated review[J]. Water Research, 2017, 114: 151-180.
- [5] XIAO K, XU Y, LIANG S, LEI T, SUN JY, WEN XH, ZHANG HX, CHEN CS, HUANG X. Engineering application of membrane bioreactor for wastewater treatment in China: current state and future prospect[J]. Frontiers of Environmental Science & Engineering, 2014, 8(6): 805-819.
- [6] 王震, 黄武, 胡程月, 刘子仪, 郭青鹏. 膜生物反应器在污水处理中的应用[J]. 四川化工, 2018, 21(6): 19-22.
WANG Z, HUANG W, HU CY, LIU ZY, GUO QP. Application of membrane bioreactor in sewage treatment[J]. Sichuan Chemical Industry, 2018, 21(6): 19-22 (in Chinese).
- [7] XIAO K, LIANG S, WANG XM, CHEN CS, HUANG X. Current state and challenges of full-scale membrane bioreactor applications: a critical review[J]. Bioresource Technology, 2019, 271: 473-481.
- [8] 张姣, 肖康, 梁帅, 黄霞. 膜技术在中国市政污水处理与再生中的应用现状与未来挑战[J]. 环境工程, 2022, 40(3): 1-6, 153.
ZHANG J, XIAO K, LIANG S, HUANG X. Membrane technologies for municipal wastewater treatment and reclamation in China: application and challenges[J]. Environmental Engineering, 2022, 40(3): 1-6, 153 (in Chinese).
- [9] MONCLÚS H, DALMAU M, GABARRÓN S, FERRERO G, RODRÍGUEZ-RODA I, COMAS J. Full-scale validation of an air scour control system for energy savings in membrane bioreactors[J]. Water Research, 2015, 79: 1-9.
- [10] 赵冰心, 黄万抚, 李睿涵. 膜生物反应器中膜污染控制的研究进展[J]. 应用化工, 2018, 47(12): 2766-2770, 2776.
ZHAO BX, HUANG WF, LI RH. Review of preventing and treating membrane fouling in membrane bioreactor[J]. Applied Chemical Industry, 2018, 47(12): 2766-2770, 2776 (in Chinese).
- [11] 倪凌峰, 王亚宜. 基于群体感应猝灭理论的 MBR 膜污染控制技术研究进展[J]. 哈尔滨工业大学学报, 2019, 51(8): 191-200.
NI LF, WANG YY. Advances in MBR biofouling control based on quorum sensing and quenching[J]. Journal of Harbin Institute of Technology, 2019, 51(8): 191-200 (in Chinese).
- [12] 张泽瀚, 洪乾坤, 刘博超, 王侃鸣, 王红宇. 群体猝灭技术在控制 MBR 生物污染中的研究进展[J]. 工业水处理, 2021, 41(4): 7-13.
ZHANG ZH, HONG QK, LIU BC, WANG KM, WANG HY. Research progress on quorum quenching technology in controlling MBR biofouling[J]. Industrial Water Treatment, 2021, 41(4): 7-13 (in Chinese).
- [13] LEE K, YU HR, ZHANG XL, CHOO KH. Quorum sensing and quenching in membrane bioreactors: Opportunities and challenges for biofouling control[J]. Bioresource Technology, 2018, 270: 656-668.
- [14] OH HS, LEE CH. Origin and evolution of quorum quenching technology for biofouling control in MBRs for wastewater treatment[J]. Journal of Membrane Science, 2018, 554: 331-345.
- [15] XU BY, SU QX, YANG YX, HUANG SJ, YANG Y, SHI XQ, CHOO KH, NG HY, LEE CH. Quorum quenching in membrane bioreactors for fouling retardation: complexity provides opportunities[J]. Environmental Science & Technology, 2024.
- [16] IORHEMEN OT, HAMZA RA, TAY JH. Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: membrane fouling[J]. Membranes, 2016, 6(2): 33.
- [17] IORHEMEN OT, HAMZA RA, TAY JH. Membrane fouling control in membrane bioreactors (MBRs) using granular materials[J]. Bioresource Technology, 2017, 240: 9-24.
- [18] YAO W, WANG Z, SONG P. The cake layer formation in the early stage of filtration in MBR: mechanism and model[J]. Journal of Membrane Science, 2018, 559: 75-86.
- [19] LE-CLECH P, CHEN V, FANE TAG. Fouling in membrane bioreactors used in wastewater treatment[J]. Journal of Membrane Science, 2006, 284(1/2): 17-53.
- [20] AZAÏS A, MENDRET J, PETIT E, BROSILLON S. Evidence of solute-solute interactions and cake enhanced concentration polarization during removal of pharmaceuticals from urban wastewater by nanofiltration[J]. Water Research, 2016, 104: 156-167.
- [21] ZARGAR M, UJIHARA R, VOGT SJ, VROUWENVELDER JS, FRIDJONSSON EO, JOHNS ML. Imaging of membrane concentration polarization by NaCl using ^{23}Na nuclear magnetic resonance[J]. Journal of Membrane Science, 2020, 600: 117868.
- [22] DU XJ, SHI YK, JEGATHEESAN V, HAQ IU. A review on the mechanism, impacts and control methods of membrane fouling in MBR system[J]. Membranes, 2020, 10(2): 24.
- [23] LIU Q, REN JY, LU YS, ZHANG XL, RODDICK FA, FAN LH, WANG YF, YU HR, YAO P. A review of the current *in situ* fouling control strategies in MBR: Biological versus physicochemical[J]. Journal of Industrial and Engineering Chemistry, 2021, 98: 42-59.
- [24] 牛承鑫, 潘阳, 陆雪琴, 甄广印, 张衷译, 宋玉, 赵由才. 厌氧膜生物反应器(AnMBR)膜污染过程及控制方法研究进展[J]. 环境化学, 2019, 38(12): 2851-2859.
NIU CX, PAN Y, LU XQ, ZHEN GY, ZHANG ZY, SONG Y, ZHAO YC. Research progress in membrane fouling process and control method of anaerobic membrane bioreactor (AnMBR)[J]. Environmental Chemistry, 2019, 38(12): 2851-2859 (in Chinese).

- [25] SPETTMANN D, EPPMANN S, FLEMMING HC, WINGENDER J. Simultaneous visualisation of biofouling, organic and inorganic particle fouling on separation membranes[J]. *Water Science and Technology*, 2007, 55(8/9): 207-210.
- [26] WANG ZW, WU ZC, YIN X, TIAN LM. Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: membrane foulant and gel layer characterization[J]. *Journal of Membrane Science*, 2008, 325(1): 238-244.
- [27] WANG ZW, MA JX, TANG CY, KIMURA K, WANG QY, HAN XM. Membrane cleaning in membrane bioreactors: a review[J]. *Journal of Membrane Science*, 2014, 468: 276-307.
- [28] ARABI S, NAKHLA G. Impact of calcium on the membrane fouling in membrane bioreactors[J]. *Journal of Membrane Science*, 2008, 314(1/2): 134-142.
- [29] ZHANG HF, FAN X, WANG B, SONG LF. Calcium ion on membrane fouling reduction and biofouling promotion in membrane bioreactor at high salt shock[J]. *Bioresource Technology*, 2016, 200: 535-540.
- [30] PHILIPPE A, SCHAUMANN GE. Interactions of dissolved organic matter with natural and engineered inorganic colloids: a review[J]. *Environmental Science & Technology*, 2014, 48(16): 8946-8962.
- [31] BOUHABILA EH, BEN AÏM R, BUISSON H. Fouling characterisation in membrane bioreactors[J]. *Separation and Purification Technology*, 2001, 22: 123-132.
- [32] SHI YH, HUANG JH, ZENG GM, GU YL, HU Y, TANG B, ZHOU JX, YANG Y, SHI LX. Evaluation of soluble microbial products (SMP) on membrane fouling in membrane bioreactors (MBRs) at the fractional and overall level: a review[J]. *Reviews in Environmental Science and Bio/Technology*, 2018, 17(1): 71-85.
- [33] JANG Y, KIM HS, HAM SY, PARK JH, PARK HD. Investigation of critical sludge characteristics for membrane fouling in a submerged membrane bioreactor: role of soluble microbial products and extracted extracellular polymeric substances[J]. *Chemosphere*, 2021, 271: 129879.
- [34] HUANG BC, GUAN YF, CHEN W, YU HQ. Membrane fouling characteristics and mitigation in a coagulation-assisted microfiltration process for municipal wastewater pretreatment[J]. *Water Research*, 2017, 123: 216-223.
- [35] 刘琛, 李亮, 钱光升, 张驰, 胡筱敏. 膜生物反应器膜污染与控制研究进展[J]. *环境保护与循环经济*, 2017, 37(10): 20-25, 35.
- [36] LIU C, LI L, QIAN GS, ZHANG C, HU XM. Research progress of membrane fouling and control in membrane bioreactor[J]. *Environmental Protection and Circular Economy*, 2017, 37(10): 20-25, 35 (in Chinese).
- [37] GUO WS, NGO HH, LI JX. A mini-review on membrane fouling[J]. *Bioresource Technology*, 2012, 122: 27-34.
- [38] STOODLEY P, SAUER K, DAVIES DG, COSTERTON JW. Biofilms as complex differentiated communities[J]. *Annual Review of Microbiology*, 2002, 56: 187-209.
- [39] SUN ZQ, XI JY, YANG CP, CONG WJ. Quorum sensing regulation methods and their effects on biofilm in biological waste treatment systems: a review[J]. *Frontiers of Environmental Science & Engineering*, 2021, 16(7): 87.
- [40] XIONG FZ, WEN DH, LI QL. Calcium-mediated regulation promotes the biofilm formation of two novel pyridine-degrading bacteria[J]. *Frontiers in Environmental Science*, 2022, 10: 815528.
- [41] 熊富忠, 赵小希, 温东辉, 李琪琳. 一株吡啶降解菌 *Pseudomonas* sp. ZX08 的生物膜形成特性及影响因素[J]. *微生物学通报*, 2020, 47(5): 1342-1353.
- [42] XIONG FZ, ZHAO XX, WEN DH, LI QL. Characteristics and influencing factors of biofilm formation by a pyridine-degrading bacterium *Pseudomonas* sp. ZX08[J]. *Microbiology China*, 2020, 47(5): 1342-1353 (in Chinese).
- [43] CHANG YR, LEE YJ, LEE DJ. Membrane fouling during water or wastewater treatments: current research updated[J]. *Journal of the Taiwan Institute of Chemical Engineers*, 2019, 94: 88-96.
- [44] CHEN CH, FU Y, GAO DW. Membrane biofouling process correlated to the microbial community succession in an A/O MBR[J]. *Bioresource Technology*, 2015, 197: 185-192.
- [45] FLEMMING HC, WUERTZ S. Bacteria and archaea on Earth and their abundance in biofilms[J]. *Nature Reviews Microbiology*, 2019, 17(4): 247-260.
- [46] PAPPENFORTH K, BASSLER BL. Quorum sensing signal-response systems in Gram-negative bacteria[J]. *Nature Reviews Microbiology*, 2016, 14(9): 576-588.
- [47] XIONG FZ, ZHAO XX, WEN DH, LI QL. Effects of N-acyl-homoserine lactones-based quorum sensing on biofilm formation, sludge characteristics, and bacterial community during the start-up of bioaugmented reactors[J]. *Science of The Total Environment*, 2020, 735: 139449.
- [48] PARSEK MR, GREENBERG EP. Sociomicrobiology: the connections between quorum sensing and biofilms[J]. *Trends in Microbiology*, 2005, 13(1): 27-33.
- [49] FLEMMING HC, WINGENDER J, SZEWZYK U, STEINBERG P, RICE SA, KJELLEBERG S. Biofilms: an emergent form of bacterial life[J]. *Nature Reviews Microbiology*, 2016, 14(9): 563-575.
- [50] WHITELEY M, DIGGLE SP, GREENBERG EP. Progress in and promise of bacterial quorum sensing research[J]. *Nature*, 2017, 551(7680): 313-320.
- [51] HUANG JH, SHI YH, ZENG GM, GU YL, CHEN GQ, SHI LX, HU Y, TANG B, ZHOU JX. Acyl-homoserine lactone-based quorum sensing and quorum quenching hold promise to determine the performance of biological wastewater treatments: an overview[J]. *Chemosphere*, 2016, 157: 137-151.
- [52] VERBEKE F, de CRAEMER S, DEBUNNE N, JANSSENS Y, WYNENDAELE E, van de WIELE C, de SPIEGELEER B. Peptides as quorum sensing molecules: measurement techniques and obtained

- levels *in vitro* and *in vivo*[J]. *Frontiers in Neuroscience*, 2017, 11: 183.
- [51] ZHAO J, QUAN CS, JIN LM, CHEN M. Production, detection and application perspectives of quorum sensing autoinducer-2 in bacteria[J]. *Journal of Biotechnology*, 2018, 268: 53-60.
- [52] HERNANDEZ DE, SINTIM HO. Quorum sensing autoinducer-3 finally yields to structural elucidation[J]. *ACS Central Science*, 2020, 6(2): 93-96.
- [53] GARCÍA-REYES S, SOBERÓN-CHÁVEZ G, COCOTL-YANEZ M. The third quorum-sensing system of *Pseudomonas aeruginosa*: *Pseudomonas* quinolone signal and the enigmatic PqsE protein[J]. *Journal of Medical Microbiology*, 2020, 69(1): 25-34.
- [54] DOW JM. Diffusible signal factor-dependent quorum sensing in pathogenic bacteria and its exploitation for disease control[J]. *Journal of Applied Microbiology*, 2017, 122(1): 2-11.
- [55] McCLEAN KH, WINSON MK, FISH L, TAYLOR A, CHHABRA SR, CAMARA M, DAYKIN M, LAMB JH, SWIFT S, BYCROFT BW, STEWART GSAB, WILLIAMS P. Quorum sensing and *Chromobacterium violaceum*: exploitation of violacein production and inhibition for the detection of N-acylhomoserine lactones[J]. *Microbiology*, 1997, 143 (Pt 12): 3703-3711.
- [56] KAWAGUCHI T, CHEN YP, NORMAN RS, DECHO AW. Rapid screening of quorum-sensing signal N-acyl homoserine lactones by an *in vitro* cell-free assay[J]. *Applied and Environmental Microbiology*, 2008, 74(12): 3667-3671.
- [57] HUANG SJ, ZHANG H, NG TCA, XU BY, SHI XQ, NG HY. Analysis of N-Acy-L-homoserine lactones (AHLs) in wastewater treatment systems using SPE-LLE with LC-MS/MS[J]. *Water Research*, 2020, 177: 115756.
- [58] HONDA R, PHAN PT, TOBINO T, PRASERTKULSAK S, PANCHAVININ S, HONG PN, TAING C, NOGUCHI M, CHIEMCHAI SRI W, CHIEMCHAI SRI C. Diversity of N-acyl homoserine lactones in activated sludge detected by Fourier transform mass spectrometry[J]. *NPJ Clean Water*, 2019, 2: 11.
- [59] LI TL, GUO F, LIN Y, LI YD, WU GX. Metagenomic analysis of quorum sensing systems in activated sludge and membrane biofilm of a full-scale membrane bioreactor[J]. *Journal of Water Process Engineering*, 2019, 32: 100952.
- [60] CAI WW, LIU Y. Enhanced membrane biofouling potential by on-line chemical cleaning in membrane bioreactor[J]. *Journal of Membrane Science*, 2016, 511: 84-91.
- [61] FENG ZL, LI TL, LIN Y, WU GX. Microbial communities and interactions in full-scale A2/O and MBR wastewater treatment plants[J]. *Journal of Water Process Engineering*, 2022, 46: 102660.
- [62] LI Z, NAIR SK. Quorum sensing: how bacteria can coordinate activity and synchronize their response to external signals?[J]. *Protein Science*, 2012, 21(10): 1403-1417.
- [63] WATSON WT, MINOGUE TD, VAL DL, von BODMAN SB, CHURCHILL MEA. Structural basis and specificity of acyl-homoserine lactone signal production in bacterial quorum sensing[J]. *Molecular Cell*, 2002, 9(3): 685-694.
- [64] NAGA NG, EL-BADAN DE, GHANEM KM, SHAABAN MI. It is the time for quorum sensing inhibition as alternative strategy of antimicrobial therapy[J]. *Cell Communication and Signaling*, 2023, 21(1): 133.
- [65] NI NT, LI MY, WANG JF, WANG BH. Inhibitors and antagonists of bacterial quorum sensing[J]. *Medicinal Research Reviews*, 2009, 29(1): 65-124.
- [66] SIKDAR R, ELIAS M. Quorum quenching enzymes and their effects on virulence, biofilm, and microbiomes: a review of recent advances[J]. *Expert Review of Anti-Infective Therapy*, 2020, 18(12): 1221-1233.
- [67] FETZNER S. Quorum quenching enzymes[J]. *Journal of Biotechnology*, 2015, 201: 2-14.
- [68] ZHOU LT, ZHANG Y, GE YZ, ZHU X, PAN JY. Regulatory mechanisms and promising applications of quorum sensing-inhibiting agents in control of bacterial biofilm formation[J]. *Frontiers in Microbiology*, 2020, 11: 589640.
- [69] PROCTOR CR, McCARRON PA, TERNAN NG. Furanone quorum-sensing inhibitors with potential as novel therapeutics against *Pseudomonas aeruginosa*[J]. *Journal of Medical Microbiology*, 2020, 69(2): 195-206.
- [70] PARK JS, RYU EJ, LI LZ, CHOI BK, KIM BM. New bicyclic brominated furanones as potent autoinducer-2 quorum-sensing inhibitors against bacterial biofilm formation[J]. *European Journal of Medicinal Chemistry*, 2017, 137: 76-87.
- [71] LIU L, WU RY, ZHANG JL, SHANG N, LI PL. D-ribose interferes with quorum sensing to inhibit biofilm formation of *Lactobacillus paraplantarum* L-ZS9[J]. *Frontiers in Microbiology*, 2017, 8: 1860.
- [72] WANG KM, LU SH, WANG YJ, ZENG XY, ZHANG ZH, LIAN XR, WANG HY. Exploring the mechanism of membrane fouling alleviation with furanone and its derivatives addition as quorum sensing inhibitors[J]. *Chemical Engineering Journal*, 2024, 494: 153157.
- [73] SU XY, XU QY, CHENG X, XU Z. Membrane biofouling control by D-ribose in membrane bioreactor[J]. *Journal of the Taiwan Institute of Chemical Engineers*, 2024, 159: 105470.
- [74] CHOO JH, RUKAYADI Y, HWANG JK. Inhibition of bacterial quorum sensing by *Vanilla* extract[J]. *Letters in Applied Microbiology*, 2006, 42(6): 637-641.
- [75] HONG PN, MATSUURA N, NOGUCHI M, YAMAMOTO-IKEMOTO R, HONDA R. Change of extracellular polymeric substances and microbial community in biofouling mitigation by continuous vanillin dose in membrane bioreactor[J]. *Journal of Water Process Engineering*, 2022, 47: 102644.
- [76] KIM J, SHIN M, SONG W, PARK S, RYU J, JUNG J, CHOI S, YU Y, KWEON J, LEE JH. Application of quorum sensing inhibitors for improving anti-

- biofouling of polyamide reverse osmosis membranes: direct injection versus surface modification[J]. *Separation and Purification Technology*, 2021, 255: 117736.
- [77] NOOR AO, ALMASRI DM, BASYONY AF, ALBOHY A, ALMUTAIRI LS, ALHAMMADI SS, ALKHAMISI MA, ALSHARIF SA, ELFAKY MA. Biodiversity of N-acyl homoserine lactonase (*aiiA*) gene from *Bacillus subtilis*[J]. *Microbial Pathogenesis*, 2022, 166: 105543.
- [78] WANG WZ, MOROHOSHI T, IKENOYA M, SOMEYA N, IKEDA T. AiiM, a novel class of N-acylhomoserine lactonase from the leaf-associated bacterium *Microbacterium testaceum*[J]. *Applied and Environmental Microbiology*, 2010, 76(8): 2524-2530.
- [79] KRYSCIAK D, SCHMEISSER C, PREUSS S, RIETHAUSEN J, QUITSCHAU M, GROND S, STREIT WR. Involvement of multiple loci in quorum quenching of autoinducer I molecules in the nitrogen-fixing symbiont *Rhizobium* (*Sinorhizobium*) sp. strain NGR234[J]. *Applied and Environmental Microbiology*, 2011, 77(15): 5089-5099.
- [80] OH HS, KIM SR, CHEONG WS, LEE CH, LEE JK. Biofouling inhibition in MBR by *Rhodococcus* sp. BH4 isolated from real MBR plant[J]. *Applied Microbiology and Biotechnology*, 2013, 97(23): 10223-10231.
- [81] WANG WZ, MOROHOSHI T, SOMEYA N, IKEDA T. AidC, a novel N-acylhomoserine lactonase from the potato root-associated *Cytophaga*-flavobacteria-*Bacteroides* (CFB) group bacterium *Chryseobacterium* sp. strain StRB126[J]. *Applied and Environmental Microbiology*, 2012, 78(22): 7985-7992.
- [82] LIN YH, XU JL, HU JY, WANG LH, ONG SL, LEADBETTER JR, ZHANG LH. Acyl-homoserine lactone acylase from *Ralstonia* strain XJ12B represents a novel and potent class of quorum-quenching enzymes[J]. *Molecular Microbiology*, 2003, 47(3): 849-860.
- [83] ROMERO M, DIGGLE SP, HEEB S, CÁMARA M, OTERO A. Quorum quenching activity in *Anabaena* sp. PCC 7120: identification of AiiC, a novel AHL-acylase[J]. *FEMS Microbiology Letters*, 2008, 280(1): 73-80.
- [84] BOKHOVE M, JIMENEZ PN, QUAX WJ, DIJKSTRA BW. The quorum-quenching N-acyl homoserine lactone acylase PvdQ is an Ntn-hydrolase with an unusual substrate-binding pocket[J]. *Proceedings of the National Academy of Sciences of the United States of America*, 2010, 107(2): 686-691.
- [85] TANNIÈRES M, BEURY-CIROU A, VIGOUROUX A, MONDY S, PELLISSIER F, DESSAUX Y, FAURE D. A metagenomic study highlights phylogenetic proximity of quorum-quenching and xenobiotic-degrading amidases of the AS-family[J]. *PLoS One*, 2013, 8(6): e65473.
- [86] WAHEED H, MEHMOOD CT, LI YW, YANG YY, XIAO YY. Genetic insights unraveling quorum quenching potential of indigenous isolates from an anaerobic membrane bioreactor[J]. *Science of The Total Environment*, 2022, 811: 152349.
- [87] CHOWDHARY PK, KESHAVAN N, NGUYEN HQ, PETERSON JA, GONZÁLEZ JE, HAINES DC. *Bacillus megaterium* CYP102A1 oxidation of acyl homoserine lactones and acyl homoserines[J]. *Biochemistry*, 2007, 46(50): 14429-14437.
- [88] JIANG W, XIA SQ, LIANG J, ZHANG ZQ, HERMANOWICZ SW. Effect of quorum quenching on the reactor performance, biofouling and biomass characteristics in membrane bioreactors[J]. *Water Research*, 2013, 47(1): 187-196.
- [89] KIM JH, CHOI DC, YEON KM, KIM SR, LEE CH. Enzyme-immobilized nanofiltration membrane to mitigate biofouling based on quorum quenching[J]. *Environmental Science & Technology*, 2011, 45(4): 1601-1607.
- [90] KIM TH, LEE I, YEON KM, KIM J. Biocatalytic membrane with acylase stabilized on intact carbon nanotubes for effective antifouling via quorum quenching[J]. *Journal of Membrane Science*, 2018, 554: 357-365.
- [91] CHEN C, YANG Y, CHOO KH, NG HY, TAKIZAWA S, HOU L. Cracking the code of seasonal seawater biofouling: enhanced biofouling control with quorum sensing inhibitor-functionalized membranes[J]. *NPJ Clean Water*, 2024, 7: 12.
- [92] XU F, BYUN T, DUSSEN HJ, DUKE KR. Degradation of N-acylhomoserine lactones, the bacterial quorum-sensing molecules, by acylase[J]. *Journal of Biotechnology*, 2003, 101(1): 89-96.
- [93] OH HS, YEON KM, YANG CS, KIM SR, LEE CH, PARK SY, HAN JY, LEE JK. Control of membrane biofouling in MBR for wastewater treatment by quorum quenching bacteria encapsulated in microporous membrane[J]. *Environmental Science & Technology*, 2012, 46(9): 4877-4884.
- [94] HAM SY, KIM HS, CHA E, PARK JH, PARK HD. Mitigation of membrane biofouling by a quorum quenching bacterium for membrane bioreactors[J]. *Bioresource Technology*, 2018, 258: 220-226.
- [95] NOORI A, KIM H, KIM MH, KIM K, LEE K, OH HS. Quorum quenching bacteria isolated from industrial wastewater sludge to control membrane biofouling[J]. *Bioresource Technology*, 2022, 352: 127077.
- [96] KIM H, NOORI A, KIM MH, LEE C, KO JH, HWANG BK, LEE K, OH HS. Biofouling mitigation of a membrane bioreactor for industrial wastewater treatment by quorum quenching[J]. *Journal of Membrane Science*, 2024, 690: 122198.
- [97] LEE CH, CHEONG WS, LEE CH, MOON YH, OH HS, KIM SR, LEE SH, LEE JK. Isolation and identification of indigenous quorum quenching bacteria, *Pseudomonas* sp. 1A1, for biofouling control in MBR[J]. *Industrial and Engineering Chemistry Research*, 2013, 52(31): 10554-10560.
- [98] XU FF, LIAO JL, HU JC, FENG YS, HUANG YY, FENG XT, LI SF. Biofouling mitigation and microbial community dynamics in the membrane bioreactor by the indigenous quorum quenching bacterium *Delftia* sp. JL5[J]. *Bioresource Technology*, 2023, 388: 129753.

- [99] LI JL, LI ZF, XIE J, XIA Y, GONG WB, TIAN JJ, ZHANG K, YU EM, WANG GJ. Quorum-quenching potential of recombinant PvdQ-engineered bacteria for biofilm formation[J]. International Microbiology, 2023, 26(3): 639-650.
- [100] LEE K, KIM YW, LEE S, LEE SH, NAHM CH, KWON H, PARK PK, CHOO KH, KOYUNCU I, DREWS A, LEE CH, LEE JK. Stopping autoinducer-2 chatter by means of an indigenous bacterium (*Acinetobacter* sp. DKY-1): a new antibiofouling strategy in a membrane bioreactor for wastewater treatment[J]. Environmental Science & Technology, 2018, 52(11): 6237-6245.
- [101] PARK H, JANG JU, PARK J, PARK H, CHOO KH, JEON J, YEO H, LEE CH, LEE K. Exploring novel quorum quenching strain: enhanced disrupting autoinducer-2 bacterial communication to combat biofouling in membrane bioreactor for wastewater treatment[J]. Chemical Engineering Journal, 2024, 486: 150173.
- [102] LI YS, TIAN T, LI BB, YU HQ. Longer persistence of quorum quenching bacteria over quorum sensing bacteria in aerobic granules[J]. Water Research, 2020, 179: 115904.
- [103] KHAN R, SHEN F, KHAN K, LIU LX, WU HH, LUO JQ, WAN YH. Biofouling control in a membrane filtration system by a newly isolated novel quorum quenching bacterium, *Bacillus methylotrophicus* sp. WY[J]. RSC Advances, 2016, 6(34): 28895-28903.
- [104] KAMPOURIS ID, KARAYANNAKIDIS PD, BANTI DC, SAKOULA D, KONSTANTINIDIS D, YIANGOU M, SAMARAS PE. Evaluation of a novel quorum quenching strain for MBR biofouling mitigation[J]. Water Research, 2018, 143: 56-65.
- [105] LIU JB, ENG CY, HO JS, CHONG TH, WANG L, ZHANG PY, ZHOU Y. Quorum quenching in anaerobic membrane bioreactor for fouling control[J]. Water Research, 2019, 156: 159-167.
- [106] KIM AL, PARK SY, LEE CH, LEE CH, LEE JK. Quorum quenching bacteria isolated from the sludge of a wastewater treatment plant and their application for controlling biofilm formation[J]. Journal of Microbiology and Biotechnology, 2014, 24(11): 1574-1582.
- [107] WANG R, AN ZJ, FAN L, ZHOU Y, SU XM, ZHU JJ, ZHANG Q, CHEN CJ, LIN HJ, SUN FQ. Effect of quorum quenching on biofouling control and microbial community in membrane bioreactors by *Brucella* sp. ZJ1[J]. Journal of Environmental Management, 2023, 339: 117961.
- [108] GE SM, YANG RX, ZHANG Y, CHANG AK, LI YR, CHEN XH, DONG XJ. A low N-acyl-homoserine lactone-degrading *Stenotrophomonas* sp. that could efficiently mitigate biofouling in a membrane bioreactor[J]. International Biodeterioration & Biodegradation, 2023, 185: 105684.
- [109] HAM S, RYOO HS, JANG Y, LEE SH, LEE JY, KIM HS, LEE JH, PARK HD. Isolation of a quorum quenching bacterium effective to various acyl-homoserine lactones: its quorum quenching mechanism and application to a membrane bioreactor[J]. Chemosphere, 2024, 347: 140735.
- [110] GE SM, YANG HT, LI YR, CHEN XH, YANG RX, DONG XJ. Mitigation of biofouling in membrane bioreactors by quorum-quenching bacteria during the treatment of metal-containing wastewater[J]. Environmental Science and Pollution Research, 2024, 31(22): 32126-32135.
- [111] LIU ZX, PANG HL, YI KX, WANG X, ZHANG W, ZHANG CY, LIU S, GU YL, HUANG JH, SHI LX. Isolation and application of *Bacillus thuringiensis* LZX01: efficient membrane biofouling mitigation function and anti-toxicity potential[J]. Bioresource Technology, 2024, 394: 130272.
- [112] XUE YM, WANG YC, LIN YT, JIANG GY, CHEN R, QIN RL, JIA XQ, WANG C. Engineering a *Pseudomonas putida* as living quorum quencher for biofilm formation inhibition, benzenes degradation, and environmental risk evaluation[J]. Water Research, 2023, 246: 120690.
- [113] KIM SR, OH HS, JO SJ, YEON KM, LEE CH, LIM DJ, LEE CH, LEE JK. Biofouling control with bead-entrapped quorum quenching bacteria in membrane bioreactors: physical and biological effects[J]. Environmental Science & Technology, 2013, 47(2): 836-842.
- [114] MAQBOOL T, KHAN SJ, WAHEED H, LEE CH, HASHMI I, IQBAL H. Membrane biofouling retardation and improved sludge characteristics using quorum quenching bacteria in submerged membrane bioreactor[J]. Journal of Membrane Science, 2015, 483: 75-83.
- [115] LEE S, LEE SH, LEE K, KWON H, NAHM CH, LEE CH, PARK PK, CHOO KH, LEE JK, OH HS. Effect of the shape and size of quorum-quenching media on biofouling control in membrane bioreactors for wastewater treatment[J]. Journal of Microbiology and Biotechnology, 2016, 26(10): 1746-1754.
- [116] LEE SH, LEE S, LEE K, NAHM CH, KWON H, OH HS, WON YJ, CHOO KH, LEE CH, PARK PK. More efficient media design for enhanced biofouling control in a membrane bioreactor: quorum quenching bacteria entrapping hollow cylinder[J]. Environmental Science & Technology, 2016, 50(16): 8596-8604.
- [117] NAHM CH, CHOI DC, KWON H, LEE S, LEE SH, LEE K, CHOO KH, LEE JK, LEE CH, PARK PK. Application of quorum quenching bacteria entrapping sheets to enhance biofouling control in a membrane bioreactor with a hollow fiber module[J]. Journal of Membrane Science, 2017, 526: 264-271.
- [118] LIU JB, ZHANG L, ZHANG PY, ZHOU Y. Quorum quenching altered microbial diversity and activity of anaerobic membrane bioreactor (AnMBR) and enhanced methane generation[J]. Bioresource Technology, 2020, 315: 123862.
- [119] LEE S, PARK SK, KWON H, LEE SH, LEE K, NAHM CH, JO SJ, OH HS, PARK PK, CHOO KH, LEE CH, YI T. Crossing the border between laboratory and field: bacterial quorum quenching for anti-biofouling strategy in an MBR[J]. Environmental Science & Technology, 2016, 50(4): 1788-1795.

- [120] LIU JB, SUN FQ, ZHANG PY, ZHOU Y. Integrated powdered activated carbon and quorum quenching strategy for biofouling control in industrial wastewater membrane bioreactor[J]. *Journal of Cleaner Production*, 2021, 279: 123551.
- [121] YU HR, LEE K, ZHANG XL, CHOO KH. Core-shell structured quorum quenching beads for more sustainable anti-biofouling in membrane bioreactors[J]. *Water Research*, 2019, 150: 321-329.
- [122] PANG HL, HUANG JH, LI X, YI KX, LI SZ, LIU ZX, ZHANG W, ZHANG CY, LIU S, GU YL. Enhancing quorum quenching media with 3D robust electrospinning coating: a novel biofouling control strategy for membrane bioreactors[J]. *Water Research*, 2023, 234: 119830.
- [123] IQBAL T, ALI SHAH SS, LEE K, CHOO KH. Porous shell quorum quenching balls for enhanced anti-biofouling efficacy and media durability in membrane bioreactors[J]. *Chemical Engineering Journal*, 2021, 406: 126869.
- [124] YI KX, HUANG JH, PANG HL, LI SZ, LIU ZX, WANG X, ZHANG W, ZHANG CY, LIU S, GU YL. Semi-interpenetrating network hydrogels-based microcapsule for quorum quenching bacteria biocontainment to enhance biofouling control in membrane bioreactor[J]. *Chemical Engineering Journal*, 2024, 486: 150103.
- [125] LI SZ, HUANG JH, YI KX, PANG HL, LIU ZX, ZHANG W, ZHANG CY, LIU S, LI JN, LIU CH, SHU WL. Silica reinforced core-shell quorum quenching beads to control biofouling in an MBR[J]. *Chemical Engineering Journal*, 2023, 460: 141725.
- [126] ALI SHAH SS, PARK H, PARK HJ, KIM J, ANGELIDAKI I, LEE C, KIM J, CHOO KH. Polyelectrolyte-silica composite quorum quenching biomedica as new antifouling agents for anaerobic membrane bioreactor treatment[J]. *Chemical Engineering Journal*, 2023, 452: 139568.
- [127] FU Y, WU JJ, WU YX, YANG BY, WANG XL, XU RH, MENG FG. Development of a novel membrane-based quorum-quenching microbial isolator for biofouling control: process performance and microbial mechanism[J]. *Bioresource Technology*, 2024, 402: 130817.
- [128] OUYANG YC, HU Y, HUANG JH, GU YL, SHI YH, YI KX, YANG Y. Effects of exogenous quorum quenching on microbial community dynamics and biofouling propensity of activated sludge in MBRs[J]. *Biochemical Engineering Journal*, 2020, 157: 107534.
- [129] ERGÖN-CAN T, KÖSE-MUTLU B, KOYUNCU İ, LEE CH. Biofouling control based on bacterial quorum quenching with a new application: Rotary microbial carrier frame[J]. *Journal of Membrane Science*, 2017, 525: 116-124.
- [130] KATEBIAN L, HOFFMANN MR, JIANG SC. Incorporation of quorum sensing inhibitors onto reverse osmosis membranes for biofouling prevention in seawater desalination[J]. *Environmental Engineering Science*, 2018, 35(4): 261-269.
- [131] XU BY, NG TCA, HUANG SJ, NG HY. Effect of quorum quenching on EPS and size-fractioned particles and organics in anaerobic membrane bioreactor for domestic wastewater treatment[J]. *Water Research*, 2020, 179: 115850.
- [132] WAHEED H, MEHMOOD CT, LI YW, DU Y, XIAO YY. Biofouling control potential of quorum quenching anaerobes in lab-scale anaerobic membrane bioreactors: foulants profile and microbial dynamics[J]. *Chemosphere*, 2023, 315: 137760.
- [133] XIONG FZ, DAI TJ, ZHENG YH, WEN DH, LI QL. Enhanced AHL-mediated quorum sensing accelerates the start-up of biofilm reactors by elevating the fitness of fast-growing bacteria in sludge and biofilm communities[J]. *Water Research*, 2024, 257: 121697.
- [134] JO SJ, KWON H, JEONG SY, LEE SH, OH HS, YI T, LEE CH, KIM TG. Effects of quorum quenching on the microbial community of biofilm in an anoxic/oxic MBR for wastewater treatment[J]. *Journal of Microbiology and Biotechnology*, 2016, 26(9): 1593-1604.
- [135] SHU NN, PARK H, ALI SHAH SS, MAMEDA N, YOO HJ, MIN JH, ANGELIDAKI I, CHOO KH. Probiotic strategy for biofouling control through direct injection of quorum-quenching bacteria into membrane bioreactors[J]. *Chemical Engineering Journal*, 2022, 438: 135572.
- [136] KIM J, BAE E, PARK H, PARK HJ, ALI SHAH SS, LEE K, LEE J, OH HS, PARK PK, SHIN YC, MOON H, NADDEO V, CHOO KH. Membrane reciprocation and quorum quenching: an innovative combination for fouling control and energy saving in membrane bioreactors[J]. *Water Research*, 2024, 250: 121035.
- [137] ALI SHAH SS, de SIMONE L, BRUNO G, PARK H, LEE K, FABBRICINO M, ANGELIDAKI I, CHOO KH. Quorum quenching, biological characteristics, and microbial community dynamics as key factors for combating fouling of membrane bioreactors[J]. *NPJ Clean Water*, 2021, 4: 19.
- [138] LEE K, PARK YJ, IQBAL T, PARK H, JUNG Y, SHIN JH, CHOO KH. Does quorum quenching matter to microbial community dynamics in long-term membrane bioreactor operation?[J]. *Water Research*, 2023, 244: 120473.
- [139] XIAO YY, WAHEED H, XIAO KK, HASHMI I, ZHOU Y. In tandem effects of activated carbon and quorum quenching on fouling control and simultaneous removal of pharmaceutical compounds in membrane bioreactors[J]. *Chemical Engineering Journal*, 2018, 341: 610-617.
- [140] XU BY, NG TCA, HUANG SJ, HE MB, VARJANI S, NG HY. Quorum quenching affects biofilm development in an anaerobic membrane bioreactor (AnMBR): from macro to micro perspective[J]. *Bioresource Technology*, 2022, 344: 126183.