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Review

Advances in the Application of Quorum Sensing to Regulate Electrode Biofilms in Bioelectrochemical Systems

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Abstract: Bioelectrochemical systems (BESs) are an emerging technology for wastewater treatment and resource recovery. These systems facilitate electron transfer between microorganisms and electrodes, enabling their application in Various fields, such as electricity production, bioremediation, biosensors, and biocatalysis. However, electrode biofilms, which play a critical role in BESs, face several challenges (e.g., a long acclimation period, low attached biomass, high electron transfer resistance, and poor tolerance and stability) that limit the development of this technology. Quorum sensing (QS) is a communication method among microorganisms that can enhance the performance of BESs by regulating electrode biofilms. QS regulation can positively impact electrode biofilms by enhancing extracellular electron transfer (EET), biofilm formation, cellular activity, the secretion of extracellular polymeric substances (EPS), and the construction of microbial community. In this paper, the characteristics of anode electrogenic biofilms and cathode electrotrophic biofilms in BESs, EET mechanisms, and the main factors affecting biofilm formation were summarized. Additionally, QS regulation mechanisms for biofilm formation, strategies for enhancing and inhibiting QS, and the application of QS regulation for electrode biofilms in BESs were systematically reviewed and discussed. This paper provides Valuable background information and insights for future research and development of BES platforms based on QS regulation of electrode biofilms.

Keywords: quorum sensing; electrode biofilms; bioelectrochemical systems; bioenergy; pollution treatment

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1. Introduction

In nature, many microorganisms exhibit electrical activity. These microorganisms, known as electroactive microorganisms (EAMs), can transfer electrons between donors and receptors both inside and outside their cells, enabling electron flow and exchange [1]. EAMs can exist as planktonic cells in suspension or form complex community structures called electroactive biofilms (EABs) by attaching themselves to solid electrodes [2]. EABs effectively use electrodes as electron acceptors or donors through a process called extracellular electron transfer (EET), resulting in the formation of electrogenic or electrotrophic biofilms [3]. Understanding the formation and functions of EABs is crucial in exploring the performance of Various types of bioelectrochemical systems (BESs), such as microbial fuel cells (MFC), microbial electrolysis cells (MEC), and microbial electrosynthesis (MES). These systems can potentially transform Various types of waste into useful products, such as electricity, hydrogen, and chemicals, and can be used in bioremediation, biosensors, and other fields [4]. However, current research has identified several challenges associated with EABs in BESs, including long domestication cycles, low biomass, high electron transfer resistance, poor tolerance, and stability issues. These challenges seriously hinder the application and development of BESs [5].

Quorum sensing (QS) is a signal transduction mechanism that exists among microbial cells. Bacteria produce and release chemical signaling molecules, which regulate gene expression, allowing them to respond to changes in cell population density and regulating

biofilm formation [6]. Numerous studies have shown the widespread application of QS in the regulation of biofilms, such as wastewater treatment [7], food preservation [8], and pathogen defense [9]. Recent studies have also highlighted the potential of QS in regulating electrode biofilms within BESs. For example, Wu et al. [10] discovered that QS signaling molecules found in extracellular polymeric substances (EPS) in sludge play a crucial role in promoting the self-assembly of anode biofilms, increasing electricity generation, and facilitating the removal of antibiotics. Similarly, Li et al. [11] revealed that QS signaling molecules can enhance the redox activity of cathode biofilms and facilitate chain extension metabolic pathways, proposing potential strategies to accelerate the formation of MES cathode biofilms. These findings confirm the enormous potential of QS in electrode biofilm regulation. However, the studies on QS in regulating electrode biofilms are still in their early stages, and there is a lack of organization and induction of existing progress in this area.

Therefore, this paper aims to first introduce the characteristics, electron transfer mechanisms, and factors influencing the formation of biofilms in BESs, specifically focusing on anode-electrogenic biofilms and cathode electrotrophic biofilms. Then, it summarizes the mechanism of QS-mediated biofilm regulation and methods for enhancing or inhibiting QS. The paper systematically reviews the application progress of QS-regulated electrode biofilms in BESs, focusing on five aspects: hydrogen generation, electricity generation, chemical synthesis, pollution treatment, and biosensors. Finally, the paper explores research directions for QS-regulating electrode biofilms, aiming to provide Valuable insights for the controlled construction of electrode biofilms in BESs.

2. Electrode Biofilms in Bioelectrochemical Systems

2.1. Anode Electrogenic Biofilms

2.1.1. Pure-Culture Biofilms

Microbes using an anode electrode as a terminal electron acceptor are called electroactive microorganisms. They attach to the electrode surface to lead to the growth and development of biofilms, forming electrogenic biofilms that can be used to collect energy, degrade organic substances, treat wastewater, and perform bioremediation. The thickness of biofilms is a key factor in the performance of MFC, and the optimal thickness is conducive to achieving higher current density [12]. Typical electroactive microorganisms include *Geobacter* sp., *Shewanella* sp., *Pseudomonas* sp., *Klebsiella* sp., *Bacillus* sp., *Escherichia* sp., *Enterobacter* sp., and *Aeromonas* sp. However, due to their different extracellular membrane-binding proteins, the thickness of biofilms Varies. For example, *Geobacter sulfurreducens* is a Gram-negative bacterium that grows in a freshwater environment and can oxidize acetate in anode culture to form uniform multilayer biofilms [13]. As Gram-positive bacteria, *Thermincola potens* form thin monolayer biofilms, producing a lower current density [14]. However, a study has shown that *Thermincola ferriacetica*, another Gram-positive bacterium, could form thicker multilayer biofilms on the anode, resulting in higher current density [14]. *Shewanella* is a facultative anaerobic bacterium belonging to several species of the family, such as *S. oneidensis* MR-1, *S.* oneidensis MR-4, *S. putrefacians*, *S. putrefacians* IR-1, and *S. loihica* PV-4, which have been reported to form anode EAB. *S. oneidensis* MR-1 can form thick and highly conductive biofilms on the electrode surface, significantly improving the electricity generation performance of MFC [15,16]. *Pseudomonas aeruginosa* ZH1 is a strain isolated from MFC mixed-culture anode biofilms. It exhibits good electricity generation performance when inoculated into MFC, with a maximum current density six times higher than that of MFC inoculated with sewage sludge [17]. Incorporating *Bacillus cereus*, a methanogenic bacterium with inhibitory activity, into anaerobic sludge can promote the formation of EAB, which effectively enhances the coulombic efficiency of MFC [18]. However, the development of pure cultures in practical MFC applications is limited due to their narrow substrate spectrum, poor stress resistance, cumbersome operation, and limited electricity generation capacity.

2.1.2. Mixed-Culture Biofilms

In contrast, microorganisms in a natural mixed culture can use Various substrates due to mutualism and division of labor. The bacteria source is easy to obtain, simple to operate, and exhibits strong resistance to adversity. Therefore, mixed-culture MFCs show great potential in practical applications. Some microorganisms in wastewater have electrochemical activity and can be directly used as inoculants for MFCs. For example, brewery wastewater contains abundant microorganisms and high levels of organic matter. When diluted brewery wastewater is inoculated into the MFC anode, the maximum power density output is 168 mW/m^2 [19]. Sludge also contains Various electroactive microorganisms. Anaerobic sludge from wastewater treatment plants is used to inoculate single-chamber MFCs, resulting in a maximum power density output of 488 mW/m^2 [20]. However, natural mixed cultures have drawbacks such as complex and Variable bacterial species, low coulombic efficiency, poor stability and reproducibility, and uncontrollability.

2.1.3. Coculture Biofilms

In recent years, the construction of artificial multicellular systems has emerged as a new approach to addressing the limitations of pure and mixed-culture electricity generation systems. In 2015, Wang et al. [21] established a planktonic cell biofilm symbiotic system using the fermentation bacteria *Escherichia coli* and the dissimilating metal-reducing bacteria *S. oneidensis* in a dual-chamber MFC anode. The results showed that the maximum current density of the cocultured MFC was 2.0 $\mu A/cm^2$, which is significantly higher than that of pure-culture MFCs. *Pseudomonas aeruginosa* and *Klebsiella Variicola* can form a coculture system based on the synergistic effect of metabolites. The metabolite 1,3-propanediol secreted by *K. Variicola* can induce *P. aeruginosa* to produce more electron mediators, thereby improving the performance of cocultured MFC [22]. Not only can cocultivation between bacteria enhance the electricity generation performance of MFCs, but bacteria and fungi can also achieve this effect. The maximum power density output of an MFC cocultured with yeast *Lipomyces starkeyi* and bacteria *Klebsiella pneumoniae* was 12.87 W/m^3, approximately three and six times higher than that of pure yeast and pure bacterial MFCs, respectively [23]. In 2017, Liu et al. [24] constructed three microbial cocultured systems for electricity generation. *S. oneidensis* can utilize *E. coli* and *Bacillus subtilis* to consume lactic acid and riboflavin produced using glucose, respectively, to generate electricity. At the same time, *S. oneidensis* can oxidize lactic acid into acetic acid as a carbon source to feed *E. coli* and *B. subtilis*, forming a cross-fed microbial community among the three strains. In 2021, Sharma et al. [25] identified three strains of bacteria, namely E1, SCS5, and B2 (isolated by their laboratory), which were inoculated with *S. putrefaciens* into the dual-chamber MFC anode. The results demonstrate that the electricity generation performance of cocultured MFC involving the four bacteria was significantly improved compared to all pure MFCs. However, in some cases, there may be antagonistic effects between cocultured microorganisms. For example, when three Gram-negative bacteria (*S. oneidensis*, *G. sulfurreducens*, and *P. aeruginosa*) are cocultured with Gram-positive bacteria, *Clostridium acetobutylicum*, the power density generated is smaller than that of each pure-culture MFC [26].

2.1.4. Extracellular Electron Transfer Mechanisms in Electrogenic Biofilms

EET is a form of microbial respiration that involves the transfer of electrons between microbial cells and extracellular solid substances. Electroactive microorganisms facilitate electrons to the anode through two main mechanisms: direct electron transfer (DET) and indirect electron transfer. Currently, EET is believed to operate through three main mechanisms: (1) short-term transfer facilitated by direct contact between microorganisms, electron acceptors, and conductive proteins (e.g., outer membrane polyheme, c-type cytochrome, and ferrithione); (2) long-distance transfer through conductive pili or nanowires [27]; and (3) secretion of soluble electron shuttles (e.g., phenazine, riboflavin, pyocyanin, melanin, and other redox substances) by microorganisms for indirect electron transfer, promoting electron transfer between EAB and extracellular receptors/donors [12].

DET requires physical contact between microorganisms and electrodes, necessitating the presence of electron transfer proteins capable of transferring electrons from the inside to the outside of the cell. C-type cytochrome, a multiheme protein on the cell membrane, assists bacteria in adhering to the anode surface. For example, *G. sulfurreducens* uses multiple protein cytochrome pathways to reduce Fe(III) through direct contact [28]. *S. oneidensis* MR-1 is among the first microorganisms identified to use minerals such as Fe(III), Mn(III), or Mn(IV) as terminal electron acceptors [29]. Electrons are transferred from quinolone (QH_2) in the plasma membrane to the bacterial surface through the cytoplasm and outer membrane, where the heme protein MtrC directly transfers electrons to surface metal atoms through heme iron atoms exposed in its solvent environment.

Studies have shown that anode biomass increases linearly with the thickness of biofilms [30], and microorganisms located away from the electrode surface can generate current through long-distance electron transport. Both *Shewanella* and *Geobacter* are capable of producing nanosized protein filaments with long diameters, known as conductive pili or nanowires, which facilitate electron transfer to the anode [31]. Cytochrome, pili, and nanowires can form dense networks within the biofilm matrix, promoting electron transfer [32].

Redox shuttles are self-secreted by microorganisms and facilitate electron transfer between external electron acceptors/donors and microorganisms. *G. sulfurreducens* biofilms secrete riboflavin, which interacts with outer membrane c-type cytochrome to mediate indirect electron transfer. The release and combination of riboflavin help maintain intracellular redox homeostasis within their biofilms [33]. *Pseudomonas aeruginosa* secretes phenazine-like substances and undergoes high-speed electron transfer to the anode in MFC systems.

2.1.5. Main Factors Affecting Electrogenic Biofilm Formation

Temperature

Biofilms grown at higher temperatures exhibit greater electrochemical activity compared to those grown at lower temperatures. High temperatures accelerate initial biofilm formation and affect the catalytic performance of these biofilms in bioelectricity generation. For example, biofilm growth at 15 °C takes 40 days, while growth at 35 °C only takes 3.5 days [34]. The effect of temperature on MFC performance can be characterized by internal resistance, where higher internal resistance corresponds to lower power density output. At 37 °C, the internal resistance of the MFC was approximately 29 Ω. When the temperature changes to 30 °C and 10 °C, the internal resistance increases by 62% and 303%, respectively, leading to corresponding changes in the maximum power density output. Specifically, at 37 °C, the maximum power density is 7.89 W/m^3, which is 199% and 24% higher than that observed at 10 °C (2.64 W/m^3) and 30 °C (6.34 W/m^3), respectively [35].

pH

pH plays a crucial role in the growth of anode-electrogenic biofilms. Research has shown that biofilms exhibit optimal growth at neutral pH levels ranging from 6 to 9, and deviations from this neutral pH range can significantly decrease biofilm performance. The average current densities of anode biofilms grown at pH 6, pH 7, and pH 9 are measured to be 151, 821, and 730 $\mu A/cm^2$, respectively [36]. In a study where a mixed culture isolated from brewery wastewater was inoculated into a dual-chamber MFC anode, it was observed that the power density output increased with an increase in anode pH Value (from pH 6 to pH 8). At pH 8, the MFC achieved the maximum power density (63.8 ± 0.65 mW/m^2) and chemical oxygen demand (COD) removal efficiency ($63.5 \pm 1.5\%$) [37]. This study suggested that alkaline conditions (pH 8) are more favorable for MFCs to treat brewery wastewater and recover electricity [19].

Electrode Modification

Modifying electrodes through surface modification is an effective strategy for regulating biofilm formation and improving BES performance. For example, faujasite zeolite-Y

(ZY) exchanged with iron (Fe) was used to modify the glassy carbon/graphite electrode (GC/gr-ZY_{Fe}), as the MFC anode could increase the maximum current density by 7.7 times compared with the bare GC/gr electrode; this improvement was attributed to a stronger hydrophilic electrode surface that facilitated the attachment of microbial cells [38]. Furthermore, partial oxidation of carbon felt through ultraviolet (UV)/O_3 treatment can enhance the biofilm formation and electron transfer of *Shewanella*, with the best biofilm performance achieved when the carbon electrode undergoes 45 min of UV/O_3 treatment [39]. The surface charge and hydrophobicity of the anode also influence the formation of biofilms, leading to significant differences in BES performance. Generally, positive charges and hydrophilicity on the electrode surface selectively enrich electroactive microorganisms (e.g., *Geobacter*) and promote the formation of electroactive biofilms. For example, modifying the surface of glassy carbon with functional groups such as –N (CH^+_3) $_3$, –OH, –SO_3^-, and–CH_3 as the anode resulted in average start-up times and final current densities of 23 days and 0.204 mA/cm^2, 25.4 days and 0.149 mA/cm^2, 25.9 days and 0.114 mA/cm^2, and 37.2 days and 0.048 mA/cm^2 [40], respectively. It has been observed that the use of negatively charged groups (carboxylates) on the electrode surface for anode modification reduces the power output of MFCs, while the introduction of positively charged groups will double the power output [41].

Electrode Potential

The oxidation–reduction potential serves as an important triggering factor for regulating EPS in microbial aggregates. In a BES reactor, mixed bacterial biofilms were cultured under different anode potentials (−0.3, 0, +0.3, and +0.6 V Vs. SCE). Biofilms grown at 0 V exhibited the highest current (7.2 mA) and EPS redox capacity, while biofilms grown at +0.6 V exhibited the lowest current (1.2 mA) and EPS redox capacity [42]. Studies have shown that at relatively low potentials (e.g., −0.2 and 0 V), the biofilm area near the electrode surface produces more extracellular redox-active proteins and fewer extracellular polysaccharides, thereby promoting EET. However, biofilms grown at relatively high potentials (e.g., 0.4 and 0.6 V) tend to form an inner layer dominated by nonconductive extracellular polysaccharides, which limits direct EET [43]. Applying an external Voltage of 1.0 V in an anaerobic digester facilitated the formation of electroactive biofilms with a thickness of approximately 10 μm on the anode. The boosted EPS secretion under external Voltage conditions consisted of protein-like substances at the anode and cathode, potentially acting as electron mediators. Notably, the exoelectrogen *Smithella* and the methanogenic archaea *Methanosaeta* were highly enriched on the anode and cathode, with relative abundances of 25.3% and 86.1%, respectively [44].

Signaling Molecules

Chen et al. [45] discovered that endogenous or exogenous QS signaling molecules can enhance the bioadhesion and electrochemical activity of mixed-culture EABs. Endogenous acyl homoserine lactones (AHL) increased the energy recovery rate of MFC from 20.5 ± 3.9% to 28.3 ± 4.1%, while the addition of exogenous AHL further increased the energy recovery rate of MFC to 36.2 ± 5.1%. However, studies demonstrate that the biomass of electrode biofilms does not necessarily correlate with improved performance, as thicker biofilms can negatively impact electrochemical activity. By employing quorum-quenching (QQ) bacteria to degrade signaling molecules secreted by anode microorganisms, the thickness of biofilms can be controlled. QQ magnetic beads were developed using *Rhodococcus* sp. BH4 and applied to the domestication of anode biofilms in mixed MFCs. It was found that the highest power density output was achieved when the thickness of the anode biofilms was controlled to be 26.6 μm [46]. In addition, antibiotics can serve as signaling molecules to regulate the formation of electrode biofilms. In 2017, Zhou et al. [47] demonstrated for the first time that antibiotics (tobramycin) affect the growth of EAB below the minimum inhibitory concentration (sub-MIC), particularly at concentrations of 0.05 and 0.1 mg/L (1/80 and 1/40 MIC). These concentrations significantly promote the formation of mixed

EAB and selectively enrich the *Geobacter* population. In addition to chemical signals, electrical signals are considered important influencing modes for regulating the formation of EAB, such as those mediated by potassium ion channels. Jing et al. [48] constructed a *G. sulfurreducens* mutant strain that was deficient in GsuK and compared it with wild-type strains. The study shows that the lack of potassium ion electrical signals inhibited the aggregation behavior of cell populations, but it did not affect the biofilm formation or electricity generation performance of individual cells. Although the exogenous addition of the potassium ion channel blocker tetraethylammonium slowed down the formation of mixed bacterial biofilms, it selectively enriched *Geobacter* over time (45.8% on day 32, 67.7% on day 60, and 78.1% on day 90), improving EET efficiency [49].

2.2. Cathode Electrotrophic Biofilms

2.2.1. Electrotrophic Biofilms

Microorganisms that can absorb electrons from solid electron donors, such as cathode electrodes, are called electrotrophic microorganisms [50]. These microorganisms use the absorbed electrons for their physiological metabolism or the synthesis of Valuable chemicals by capturing electrons from the cathode [51]. The cathodic reduction reaction is the final step of the electrochemical reaction in BESs. It can be classified into aerobic and anaerobic reactions based on the terminal electron acceptor (TEA). According to research, CO_2, nitrates, sulfates, metal ions, protons, and organic acids can serve as TEA in anaerobic cathodes, while O_2 serves as TEA in aerobic cathodes [52]. Sulfate-reducing bacteria (SRB) are anaerobic bacteria capable of using sulfate or sulfur as TEA, and they can form EAB in MFC cathodes [53]. Some SRB strains, such as *Desulfovibrio desulfuricans* 27,774, can use not only sulfate but also nitrate as an electron acceptor, leading to the formation of uniform biofilms on the surface of stainless steel and graphite electrodes with electrocatalytic activity for oxygen reduction [54]. Furthermore, *Geobacter*, which possesses bidirectional electron transfer capability, can also absorb captured electrons on the cathode to reduce Various electron acceptors like fumarate and chloride [55]. In addition, many electrotrophic microorganisms, such as *P. aeruginosa*, *P. fluorescens*, *S. putrefaciens*, *E. coli*, *Kingella denitrificans*, *Enterobacter cloacae*, *Micrococcus luteus*, *Moraxella catarrhalis*, *B. subtilis*, and *Burkholderia cepacian*, can reduce O_2 to H_2O on the cathode of MFC. Some of these bacteria possess bidirectional electron transfer functionality and are also considered electrogenic microorganisms [56].

In addition to using electrotrophic microorganisms to catalyze the reduction reaction of the cathode in MFCs, MES can further provide the cathode electrotrophic microorganisms with the necessary reducing power to catalyze the synthesis of high-value chemicals such as H_2, CH_4, and other alcohols and acids through the input of external electric energy [57]. For instance, by applying a potential of −0.9 V (vs. Ag/AgCl) to the MES cathode, *Rhodobacter sphaeroides* can form biofilms on the cathode surface while generating H_2 (328 mL/L/d) and absorbing CO_2 (0.1 L/L/d) [58]. The addition of different electron mediators, such as neutral red, 2-hydroxy-1,4-naphthaloquinone, and hydroquinone, to the MES system with anaerobic sludge can enhance acetic acid synthesis [59]. Regular supplementation of 2-hydroxy-1,4-naphthaloquinone can result in the formation of thicker and more electrocatalytically active electrotrophic biofilms [60]. Compared to pure and mixed cultures, artificial multicellular systems also offer certain advantages in the BES cathode. For example, when the Fe(0) corrosion strain IS4 and *Methanococcus maripaludis* are cocultured on the MES cathode, they can effectively convert electron-catalyzed CO_2 to synthesize methane without accumulating intermediates. On the other hand, the pure culture of *Acetobacterium woodii* cannot consume current to produce acetic acid, but when cocultured with the Fe(0) corrosion strain IS4, stable acetic acid synthesis can be achieved for more than two weeks [61].

2.2.2. Extracellular Electron Transfer Mechanisms in Electrotrophic Biofilms

Electrotrophic microorganisms employ three different pathways to absorb electrons from the cathode: (1) direct electron uptake from the electrode surface; (2) indirect electron uptake through soluble redox media; and (3) electron absorption Via the oxidation of H_2. These electron transfer mechanisms share similarities with anode-based EETs, but the involved components' functions Vary at different potentials. *G. sulfurreducens* is an effective catalyst for the cathode reduction process, which can directly absorb electrons from the electrode through c-type cytochrome and nanowires [3]. Research has shown that the reverse metal-reducing (Mtr) pathway is involved in transferring electrons from the cathode to *Shewanella* cells [62]. Electrotrophic biofilms formed by *S. oneidensis* MR-1 at the cathode undergo electron transfer through structural proteins and cytochromes. Indirect EET mechanisms do not require physical contact between microorganisms and the cathode; instead, electron transfer occurs through self-secretion or externally added redox media. Electrotrophic microorganisms can promote their electron absorption from the cathode through several redox media, such as neutral red, 2-hydroxy-1,4-naphthoquinone, and hydroquinone [59]. At the cathode, H_2 can be generated through water electrolysis and proton reduction, which can act as an electron shuttle to transfer electrons from the cathode to microbial cells. The final electron acceptor can include nitrate, sulfate, CO_2, and other compounds. Microbial metabolism, driven by H_2, can form Various products [63].

2.2.3. Main Factors Affecting Electrotrophic Biofilm Formation

Electrode Modification

The MES cathode plays a crucial role in providing electrons for the reduction of CO_2, and modifying the cathode can increase the reaction rate, thereby increasing the product yield. For example, the use of a foam copper composite cathode can increase the conversion rate of CO_2 and acetic acid output by more than twenty-one times. Similarly, oxidation–reduction graphene and copper composite cathode biofilms dominated by *Streptococcus* can increase acetic acid production by more than forty-three times [64]. Modifying carbon felt with nickel phosphide can lead to the formation of thicker biofilms in *Clostridium ljungdahlii*, resulting in an increase of 1.7 and 2.5 times in the yields of acetic and butyric acid, respectively [65]. Carbon cloth coated with the conductive polymer poly (3,4-ethylenedioxythiophene) (PEDOT) and graphite oxide has high conductivity. When applied as a modified electrode in MES to catalyze the reduction of CO_2, it promotes the formation of methanogenic biofilms, and the methane yield can reach 315.3 ± 13.2 mmol/m^2/d [66]. Additionally, modifying electrodes with electron mediators, such as coating carbon paper with neutral red or methyl Viologen, can enhance electron transfer. Methyl Viologen produces biofilms with more porous structures and higher acetic acid yields compared to neutral red [67].

Electrode Potential

The electrode potential is another key factor affecting the performance of biological cathodes in BESs. Ameen et al. [68] found that different electrode potentials have a certain impact on the formation of electrotrophic biofilms and the synthesis of acetic acid. Lowering the cathode potential (-0.51 to -0.61 V) enhances the formation of electrotrophic biofilms, but further reduction (to -0.91 V) has a negative impact on biofilm density. MES achieves the highest acetic acid yield at a potential of -0.49 V. SRB can promote electron transfer in electrotrophic biofilms and increase acetic acid yield. Xiang et al. [69] studied the electronic competition between acetic acid-producing bacteria (HB) and SRB at different cathode potentials (-0.5, -0.6, -0.7, and -0.8 V) and its impact on MES performance. The addition of sulfate enhanced the electrochemical activity of electrotrophic biofilms at all potentials. At -0.7 and -0.8 V, the biomass of *Acetobacterium* and *Desulfovibrionaceae* in the sulfate group was much higher than that in the sulfate-free group. Li et al. [70] found that the initiation cathode potential determines the electron transfer behavior of the biocathode. Biocathodes

initiated at −0.7 and −0.8 V mainly participate in the DET pathway, while those initiated at −0.9, −1.0, and −1.1 V mainly participate in the indirect electron transfer pathway.

Signaling Molecules

Research has shown that AHLs could also promote the activation of cathode electrotrophic biofilms. The addition of exogenous AHLs, like N-hexanoyl-L-homoserine lactone (C6-HSL) and N-(3-oxdodecanoyl)-L-homoserine lactone (3OC12-HSL), can increase the biomass, cell Viability, and EPS abundance of the cathode EAB of *Geobacter soli* and the redox activity of the EPS outermost protein. This results in a higher activation efficiency of the biofilms [71]. QS can also impact the EET of the MES cathode and the reduction of CO_2 to acetic acid. Regulating with exogenous C6-HSL leads to higher current output, acetic acid production, and electron recovery efficiency in the biocathode. Additionally, the proportion of H_2-generating bacteria in the cathode microbial community increases, and H_2 mediation promotes CO_2 reduction and acetic acid synthesis [72]. The addition of N-butyryl-L homoserine lactone (C4-HSL) as a typical QS signaling molecule to the MEC biocathode for treating sulfate-containing wastewater has been proven to improve the sulfate reduction efficiency and stability of the biocathode, with a 22% increase in the proportion of living cells on the biofilms [73].

Other Factors

Several other factors influence the growth of cathode electrotrophic biofilms, including temperature, pH, and dissolved oxygen. Research has shown that thermophilic conditions are more conducive to the formation of biofilms on the cathode surface. Acetic acid production in mixed-culture MES is higher at 25 °C (525.84 ± 1.55 mg/L) compared to 35 °C (49.21 ± 0.49 mg/L) due to the formation of some by-products at higher temperatures, including propionic acid, butyric acid, and H_2 [74]. The acidic environment in the cathode of BES can promote the electrocatalytic dechlorination of 2,4-dichlorophenol, achieving 100% dechlorination at pH 5 but only 88% dechlorination at pH 7 [75]. In anaerobic MFCs, the addition of the cyanobacterium *Spirulina* increases the dissolved oxygen concentration and thickens the cathode biofilms. Microbial community analysis has revealed that 50% of the electrotrophic bacteria are composed of aerobic and microaerobic genera, such as *Halomonas* and *Pseudomonas* [76].

3. Quorum Sensing Regulation for Biofilm Formation

3.1. Quorum Sensing Regulation Mechanisms

Bacteria can synthesize signaling molecules called autoinducers (AI), which can monitor changes in the number of themselves or other bacteria in the surrounding environment based on the concentration of specific signaling molecules. When the signal reaches a certain concentration threshold, it can activate the expression of related genes in the bacteria to adapt to environmental changes [77]. As shown in Figure 1, based on the different signaling molecules synthesized by bacteria and sensing mechanisms, the QS system can be divided into three representative types: (1) Gram-negative bacteria generally use AHL as signaling molecules; (2) Gram-positive bacteria generally use autoinducing peptides (AIP) as signaling molecules; and (3) both Gram-negative and positive bacteria can produce AI-2 signaling molecules.

Vibrio fischeri was the earliest Gram-negative bacterium discovered and studied in the QS system. In the 1980s, the first AHL, N-3-oxoacetyl-L homoserine lactone (3OC6-HSL), was discovered in *V. fischeri*, which controls the expression of luminescent genes through the LuxI/LuxR system [78]. Another type of Gram-negative bacteria that has been extensively studied is *P. aeruginosa*, which has two QS systems based on AHL: LasR/LasI and RhlR/RhlI systems composed of transcriptional regulatory proteins (LasR and RhlR) and autoinducing synthetases (LasI and RhlI), respectively. In recent years, it has been discovered that *P. aeruginosa* also has a non-AHL-mediated QS system, 2-heptyl-3-hydroxy-4-quinolone (Pseudomonas quinolone signaling, PQS), which can connect the Las and Rhl

systems [77]. According to reports, bacteria using AHL as signaling molecules include *Agrobacterium tumefaciens*, *Pseudomonas putida*, *Serratia liquefacians*, *Burkholderia cepacia*, and other 25 Gram-negative bacteria [79].

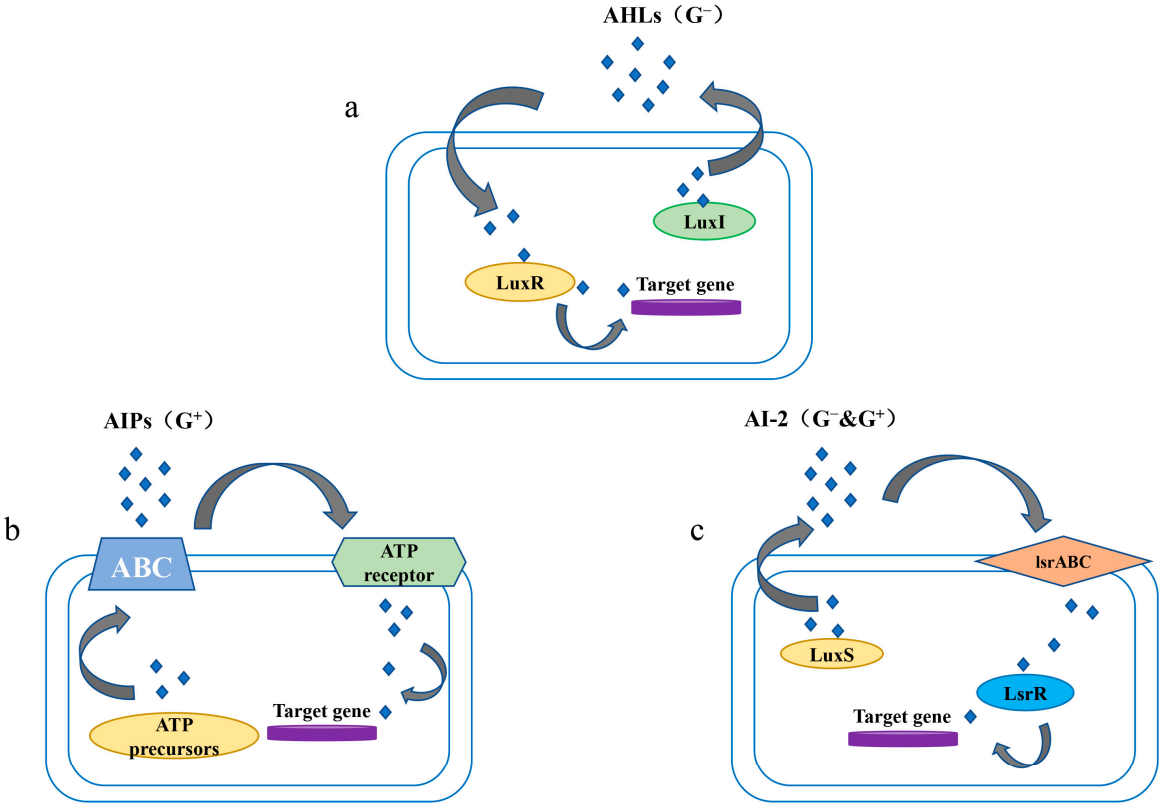

Figure 1. Schematic diagram of QS regulation based on different signaling molecules: (**a**) QS regulation based on AHLs; (**b**) QS regulation based on AIPs; and (**c**) QS regulation based on AI-2.

AIP is a small post-transcriptional modified peptide produced by Gram-positive bacteria. The synthesis of AIP signals starts in the cell ribosome and tends to mature through the role of the ATP-binding cassette transport protein complex. After the mature peptide is released from bacteria, it promotes the phosphorylation of receptor proteins and the binding of deoxyribonucleic acid-specific sites, thus activating target genes to perform specific functions. AIP can detect bacterial density, affect biofilm formation, and regulate intercellular communication [80]. According to reports, *Staphylococcus aureus*, *Lactobacillus plantarum*, *Clostridium difficile*, *C. botulinum*, *C. perfringens*, *Enterococcus faecalis*, *Listeria monocytogenes*, etc. all communicate information through AIP [81].

The AI-2 produced by the gene *lux*S is one of the most important signaling molecules in interspecific communication, and bacteria can use these signaling molecules to perceive the number of other bacteria to regulate their behavior or regulate biofilm adhesion [82]. According to reports, *Vibrio cholera*, *V. harveyi*, *Salmonella typhi*, *E. coli*, and *Deinococcus radiodurans* use the AI-2 signaling pathway [81].

3.2. Strategies for Quorum Sensing Enhancement

The QS enhancement methods can increase the content of QS signaling molecules in biofilms, which is beneficial for the start-up and operation of biological treatment systems. Table 1 presents three QS enhancement methods.

Table 1. QS enhancement strategies and their effects on the performance of biological treatment systems.

QS Enhancement Strategy	Additive	Additive Amount	Bioreactor/Microorganisms	Performance Impact	Reference
Addition of exogenous QS signaling molecules	3OC12-HSL	10 μM	MFC/Mixed culture	Energy recovery increased by 76.6% and start-up time was reduced by 9 days.	[45]
	C6-HSL	50 μM	MES/Mixed culture	Current output increased by 29.3%, and acetic acid production increased by 94.8%.	[72]
	3OC6-HSL	10 mM	MEC/Mixed culture	Hydrogen production increased by 81.8%, and electron recovery efficiency increased by 98.3% with an applied Voltage of 0.4 V.	[83]
	C4-HSL	10 μM	MFC/*P. aeruginosa*	The electricity generation of *las*I and *rhl*I mutant strains increased to a level similar to that of wild-type strains ($\approx$ 0.1 μA/cm^2).	[84]
	C6-HSL and 3OC6-HSL	0.1 μM/1 μM	MBR/Mixed culture, and *Paracoccus* sp. BW001	The protein content of biofilms increased by 62.4% (0.1 μM) and 80.1% (1 μM) on the 8th day.	[85]
Addition of synthetic promoters for QS signaling molecules	Boron	60 μM	BEFC/*Choricystis* sp.	The Voltage and MPD increased by 83.3% and 37.4%, respectively.	[86]
	Fulvic acid	1 mM	Anammox system/Mixed culture	The total inorganic nitrogen removal efficiency increased by 52.8%.	[87]
Cultivation of QS bacteria	Seven AHLs producing bacteria (Z1, K5, K33, Z20, K46, K55, and K58)	1/70 (v/v)	SBR/Mixed culture	The maximum concentrations of C6-HSL, C8-HSL, and 3OC8-HSL increased by 23%, 81%, and 27%, respectively.	[88]
	Pseudomonas aeruginosa	1/10 (v/v)	MFC/*P. aeruginosa*	The current of PQS-overexpressing mutant strains decreased by about two times compared to that of PQS-deficient mutant strains.	[84]
	Sphingomonas rubra sp.	1/100 (v/v)	MBBR/Mixed culture	No significant improvement in COD and NH_4^+-N removal efficiencies.	[89]

3.2.1. Addition of Quorum Sensing Signaling Molecules

The most common method to enhance QS is by directly adding exogenous QS signaling molecules, with AHL being the most commonly used signaling molecule. Research has shown that exogenous AHL could enhance the electrochemical activity of EAB. For instance, the addition of exogenous 3OC12-HSL increased the energy recovery rate of MFC from 20.5 $\pm$ 3.9% to 36.2 $\pm$ 5.1% and shortened the start-up period from 13 to 4 days. Moreover, AHL addition resulted in a higher relative abundance of the typical EAM *Geobacter* sp. [45]. Similarly, the regulation of exogenous C6-HSL led to increased live cell generation on the MES cathode, promoting electron transfer and achieving higher current output and acetic acid production [72]. Cai et al. [83] regulated the microbial community on the MEC electrode by adding 3OC6-HSL to enhance electron transfer between biofilms and electrodes, thereby improving the overall performance of the reactor, including hydrogen generation rate and electron recovery efficiency. Yang et al. [84] found that exogenous C4-HSL can restore the electricity generation of *P. aeruginosa las*I and *rhl*I mutant strains to a level similar to that of wild-type strains, with almost no effect on wild-type strains. Xiong et al. [85] added two exogenous AHLs (C6-HSL and 3OC6-HSL) to a biofilm reactor, significantly accelerating the biofilm formation process and resulting in thick and stable biofilms on the carrier. Additionally, it was found that AHL had little effect on the degradation ability of pyridine in the biofilm reactor but promoted the removal of $NH_4^+ - N$. However, the cost of directly adding exogenous QS signaling molecules is too high, and the stability of the system is weakened due to the rapid degradation of these molecules by some QQ bacteria.

3.2.2. Addition of Synthetic Promoters for Quorum-Sensing Signaling Molecules

Another method to enhance QS is to add signaling molecules synthesis promoters, including precursors of QS signaling molecules and their released promoters, to the bioreactor. For example, boron is a common promoter in QS signaling molecules, forming a complex with 4,5-dihydroxy-2,3-pentanedione (DPD) as a precursor for AI-2 activation. Adding boron to the bioelectrochemical fuel cell (BEFC) increased the Voltage from 18 to 33 mV and the microbial power densities (MPD) from 32.9 to 45.2 mW/m^2 [86]. In addition, fulvic acid is one of the accelerators for AHL release. In anaerobic ammonia oxidation systems, adding 1 mM fulvic acid can increase the total inorganic nitrogen removal rate from 1.27 to 1.94 mg-N/L/h. At the same time, the addition of fulvic acid can improve the activity of anaerobic ammonia-oxidizing bacteria and the production of EPS [87].

3.2.3. Cultivation of Quorum-Sensing Bacteria

Compared to directly adding exogenous QS signaling molecules or promoters, cultivating QS bacteria found in nature is a more economical method. Zhang et al. [88] isolated seven AHL-producing bacteria (*Microbacterium azadirachtae* Z1, *Caulobacter* sp. K5, *Novosphingobium* sp. K33, *Sphingomonas* sp. Z20, *Caulobacter* sp. K46, *Caulobacter Vibrioides* K55, and *Sphingomonas* sp. K58) from aerobic granular sludge. They added the bacterial supernatant to a sequencing batch reactor (SBR), resulting in a maximum concentration increase of 23%, 81%, and 27% for C6-HSL, N-octyl-L homoserine lactone (C8-HSL), and N (3-oxooctyl-L homoserine lactone (3OC8-HSL), respectively. However, research has shown that the signaling molecules produced by QS bacteria might not necessarily promote microbial EET. Yang et al. [84] inoculated three different *P. aeruginosa* strains (a wild-type strain, a PQS-deficient *pqs*A mutant strain, and a PQS-overexpressing *pqs*L mutant strain) into MFCs. The experimental results showed that the current obtained by the MFC of the *pqs*A mutant strain was much higher than that of the *pqs*L mutant strain, indicating that overexpression of PQS signaling molecules did not significantly contribute to the EET of *P. aeruginosa*. At the same time, adding QS bacteria may not necessarily have an ideal effect on pollutant removal. Wang et al. [89] did not significantly improve the removal efficiency of COD and NH_4^+-N by adding QS bacteria, *Sphingomonas rubra* sp., to the moving bed biofilm reactors (MBBRs) in the short term. AHLs may ultimately affect the removal of pollutants by affecting the bacterial community structure, so short-term addition has no significant impact on the removal of easily degradable pollutants.

3.3. Strategies for Quorum Sensing Inhibition

QS inhibition methods can suppress the action of QS signaling molecules by degrading them, inhibiting their synthesis, or interfering with their functions in biological processing systems. Table 2 presents four QS inhibition methods.

3.3.1. Cultivation of Quorum-Quenching Bacteria

A common QS inhibition method is to cultivate QQ strains to degrade QS signaling molecules. Noori et al. [90] first isolated QQ strains from industrial wastewater-activated sludge containing toxic substances such as tetramethylammonium hydroxide and 1-methyl-2-pyrrolidone. Two QQ strains of *Bacillus* (SDC-U1 and SDC-A8) survived and effectively degraded QS signals in the presence of tetramethylammonium hydroxide while slowing down the formation of mixed-culture biofilms and *P. aeruginosa* PAO1. Due to its QQ activity, *Penicillium restrictum* can reduce membrane fouling. The addition of *P. restrictum* in the hollow-fiber membrane bioreactor (HF-MBR) significantly improves the removal rates of sulfamethoxazole and erythromycin, reducing transmembrane pressure and membrane blockage [91]. The QQ bacteria *Rhodococcus* sp. BH4 can degrade signaling molecules secreted by MFC anode microorganisms, thereby controlling the thickness of the anode biofilms. The thickness of the anode biofilms in MFC with 20, 40, and 80 mg *Rhodococcus* sp. BH4 was 103.9, 26.1, and 11.2 μm, respectively. The MPD is highest when the thickness of the biofilms is 26.1 μm, which increased by 181.7% compared to the control group [46].

Taskan et al. [92] isolated four strains of bacteria with QQ activity (*Bacillus methylotrophicus* BT1, *Klebsiella pneumoniae* BT2, *Lysinibacillus fusiformis* BT3, and *Achromobacter xylosoxidans* BT4) from Various environments such as leachate, sediment sludge, and anaerobic sludge. By suppressing the QS communication between bacteria in the membrane-aerated biofilm reactor (MABR) to provide the optimal biofilm thickness, the COD removal rate in the MABR containing BT1 increased by 74.5% compared to the control group. Immobilization of a new type of QQ bacterium, *Lactobacillus* sp. SBR04MA suspension (OD600 = 1.0), in alginate beads and subsequently adding it to MBR can degrade 50 μM C6-HSL within 9 h, thereby achieving the highest membrane critical flux (24.25 $L/m^2/h$) and reducing the biofilm contamination rate [93].

3.3.2. Addition of Quorum Sensing Inhibitors

QS inhibitors inhibit QS action by interfering with QS receptors or inactivating QS signaling molecules. For instance, the addition of 100 μg/L QS inhibitor to MBR resulted in a 50% decrease in biofilm formation and a 30% decrease in AI-2 concentration, thereby effectively inhibiting biofilm formation on the membrane surface [94]. The derivatives of cinnamic acid, 4-dimethylaminocinnamic acid (DCA), and 4-methoxycinnamic acid (MCA) have been identified as potential QS inhibitors in *Chromobacterium Violaceum* ATCC12472. DCA (100 μg/mL) and MCA (200 μg/mL) can inhibit the level of N-decanoyl-homoserine lactone (C10-HSL) produced by *C. Violaceum* and reduce the production of some Virulence factors [95]. According to reports, QS inhibitors such as azorubicin [8], cinnamon, marjoram, thyme, and cloves [96], methyl ortho aminobenzoate [97], and gingerol [98] have played important roles in the food industry. The addition of easily synthesized and economically Viable QS inhibitors can help reduce operating costs, making it a more economical alternative than cultivating QQ strains.

3.3.3. Use of Quorum Sensing Signaling Molecule-Degrading Enzymes

Adding enzymes directly to biological treatment systems to degrade QS signaling molecules is an emerging QS inhibition method. Currently, many enzymes used for QS signaling molecule degradation have been discovered and studied, particularly for AHL degradation. Lactase, acylase, decarboxylase, and deaminase are four typical enzymes with AHL degradation abilities [99]. Among these four enzymes, acylase is the most commonly used. Yeon et al. [100] fixed acylase in sodium alginate to prepare a magnetic enzyme carrier, which alleviated the biological pollution of laboratory-scale MBR (membrane flux of 15 $L/m^2/h$) and enhanced membrane permeability. The maximum transmembrane pressure was 14 kPa at ~45 h, while the transmembrane pressure of the control group was 40 kPa at 55 h. Jiang et al. [101] further revealed the mechanism of immobilized acylase controlling membrane fouling in MBR. The addition of acylase to MBR can effectively reduce the concentration of QS signaling molecules, resulting in removal rates of COD and ammonia nitrogen exceeding 95%. Moreover, the scaling rate of the experimental MBR group was only 12% (0.075 kPa/h) compared to the control group (0.611 kPa/h). The research shows that QQ led to an increase in sludge settleability, a decrease in EPS, and a decrease in apparent Viscosity and relative hydrophobicity, all of which may lead to a decrease in biofilms and an increase in membrane permeability in MBR.

3.3.4. Use of Reactive Oxygen Species

In recent years, the production of reactive oxygen species (ROS), such as hydroxyl radicals and superoxide, has become increasingly popular as a new QS inhibition method. Mehmood et al. [102] fixed TiO_2 nanoparticles in porous polymers as photocatalysts and put them into the up-flow anaerobic sludge blanket-photocatalytic membrane reactor (UASB-PMR) system to explore photocatalytic QQ strategies. Under intermittent UV irradiation (accounting for 17% of the total operating time), the membrane fouling control efficiency of this new system is seven times higher than that of the UV photolysis QQ system. Continuous UV light irradiation significantly alleviated the biological fouling

of the membrane. The ROS generated by UV excitation of TiO_2 not only oxidized the pollutants on the membrane surface but also quenched the QS signaling molecules AHLs (C6-HSL, C8-HSL, C12-HSL, 3OC6-HSL, 3OC8-HSL, and 3OC12-HSL), thereby delaying membrane fouling to the maximum extent possible. The ROS generated by MBR under an applied electric field (0.8 V/cm) reduced the concentration of AHLs (C6-HSL, C8-HSL, 3OC8-HSL, and 3OC12-HSL) to as low as 13–23 ng/L, and its degradation rate was twice that of the control group. The research shows that the decrease in AHL concentration at a Voltage of 0.1–0.8 V/cm was consistent with the increase in H_2O_2 concentration. H_2O_2 may contribute to the degradation of AHLs in electrochemical MBR (eMBR), thereby reducing the production of EPS and inhibiting the formation of biofilms, leading to delayed membrane fouling [103].

Table 2. QS inhibition strategies and their effects on the performance of biological treatment systems.

QS Inhibition Strategy	Additive	Additive Amount	Bioreactor/Microorganisms	Performance Impact	Reference
Cultivation of QQ bacteria	*Bacillus* (SDC-U1 and SDC-A8)	OD_{600}1.0/OD_{600}0.5	MBR/Mixed culture or *P. aeruginosa* PAO1	Complete degradation of C8-HSL in the presence of tetramethylammonium hydroxide.	[90]
	Penicillium restrictum	2.5, 5, and 10 mg	HF-MBR/Mixed culture	Sulfamethoxazole and erythromycin removal efficiencies increased by 4.39% and 4.86%, respectively.	[91]
	Rhodococcus sp. BH4	20, 40, and 80 mg	MFC/Mixed culture	MPD increased by 181.7% in the MFC containing 40 mg BH4.	[46]
	Bacillus methylotrophicus BT1, *Klebsiella pneumoniae* BT2, *Lysinibacillus fusiformis* BT3, and *Achromobacter xylosoxidans* BT4	60 mg	MABR/Mixed culture	COD removal efficiency increased by 74.5% in the MABR containing BT1.	[92]
	Lactobacillus sp. SBR04MA	OD_{600}1.0	MBR/Mixed culture	Degrading 50 μM C6-HSL, achieving the highest critical membrane flux (24.25 L/m^2/h), and reducing biofilm fouling rate.	[93]
Addition of QS inhibitors	3,3′,4′,5-tetrachlorosalicylanilide	100 μg/L	MBR/Mixed culture	The biofilm and AI-2 concentrations were reduced by 50% and 30%, respectively.	[94]
Use of QS signaling molecule-degrading enzymes	Acylase	0.05% *v*/*v*	MBR/Mixed culture	The maximum transmembrane pressure was reduced by 26 kPa.	[100]
	Acylase	1 mg/mL	MBR/Mixed culture	The removal efficiencies of COD and ammonia nitrogen exceeded 95%; the fouling rate was 12% of that in the control.	[101]
Use of reactive oxygen species	Intermittent ultraviolet irradiation	15 W (17% of total operation time)	UASB-PMR/Mixed culture	The control efficiency of membrane fouling was seven times higher than that with the UV photolysis system.	[102]
	Electric field	0.8 V/cm	eMBR/Mixed culture	AHL degradation efficiency was twice that of the control.	[103]

4. Application of Quorum Sensing Regulation for Electrode Biofilms in Bioelectrochemical Systems

As shown in Table 3, the application of QS-regulated electrode biofilms in BES is summarized in five aspects: hydrogen generation, electricity generation, chemical synthesis, pollution treatment, and biosensors. Currently, QS regulation of electrode biofilms is mainly divided into two approaches: QS enhancement and QS inhibition. QS enhancement is mainly achieved through the addition of exogenous signaling molecules and genetic engineering modifications, as shown in Figure 2. By increasing electron transfer (such as enhancing electron mediator secretion and enhancing electron transfer pathways), promoting the rapid formation of biofilms, improving biofilms characteristics (such as increasing biomass, optimizing membrane structure, and enhancing cell activity), activating biochemical metabolism of biofilms, improving the secretion of EPS in biofilms (such as promoting

EPS secretion, increasing the abundance of proteins in EPS, and increasing the redox activity of EPS), improving the structure of microbial communities, and enriching functional microbial communities (such as electroactive bacteria, hydrogen-producing bacteria, and chain elongation bacteria), ultimately enhances BES performance. On the other hand, QS inhibition is mainly achieved by applying an electric field, adding QQ bacteria, and signaling molecules that degrade enzymes. It enhances BES performance by reducing EPS secretion, controlling biofilm thickness, and enriching electroactive bacteria. QS enhancement has more applications for regulating electrode biofilms to enhance BES performance.

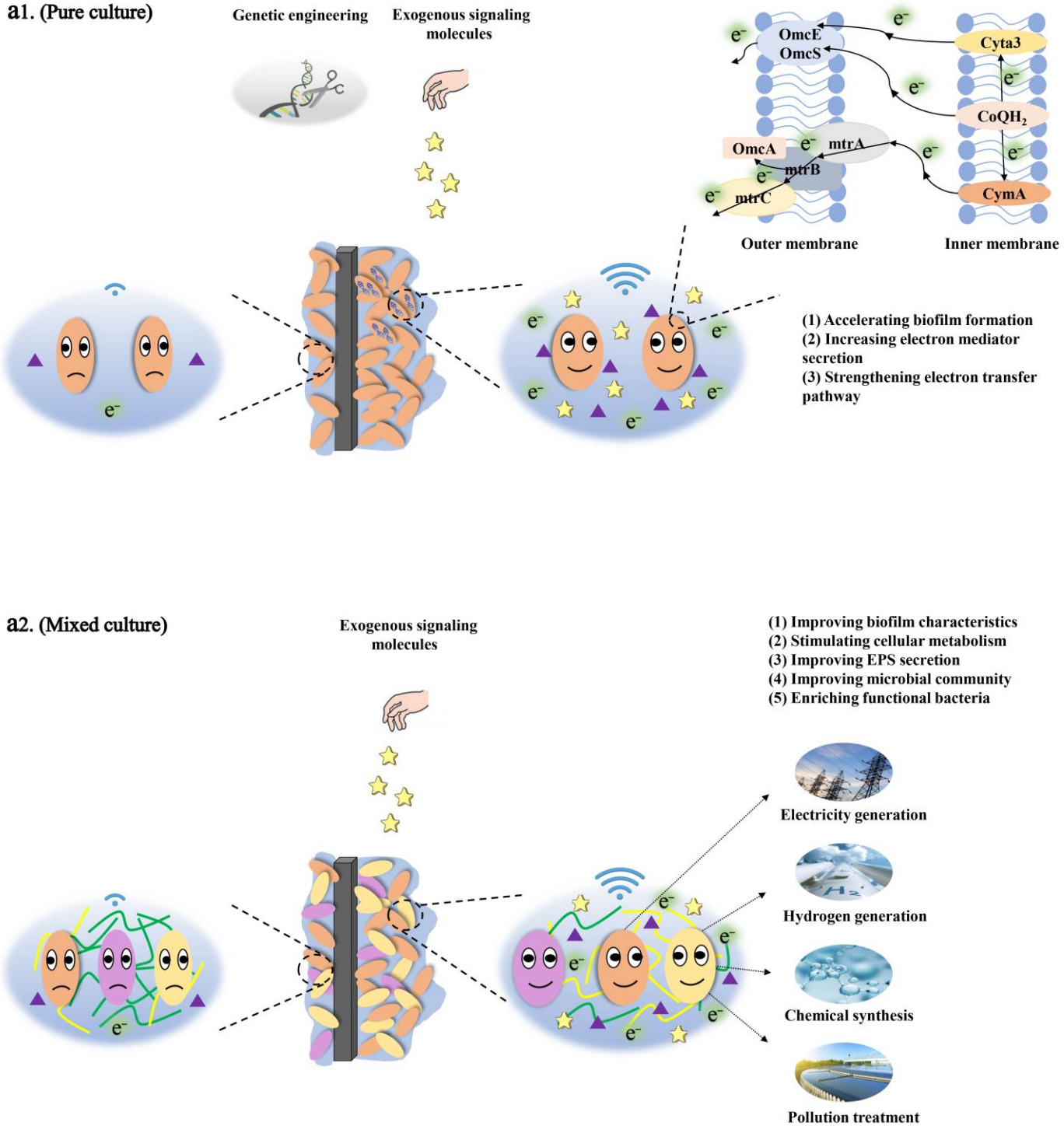

Figure 2. *Cont.*

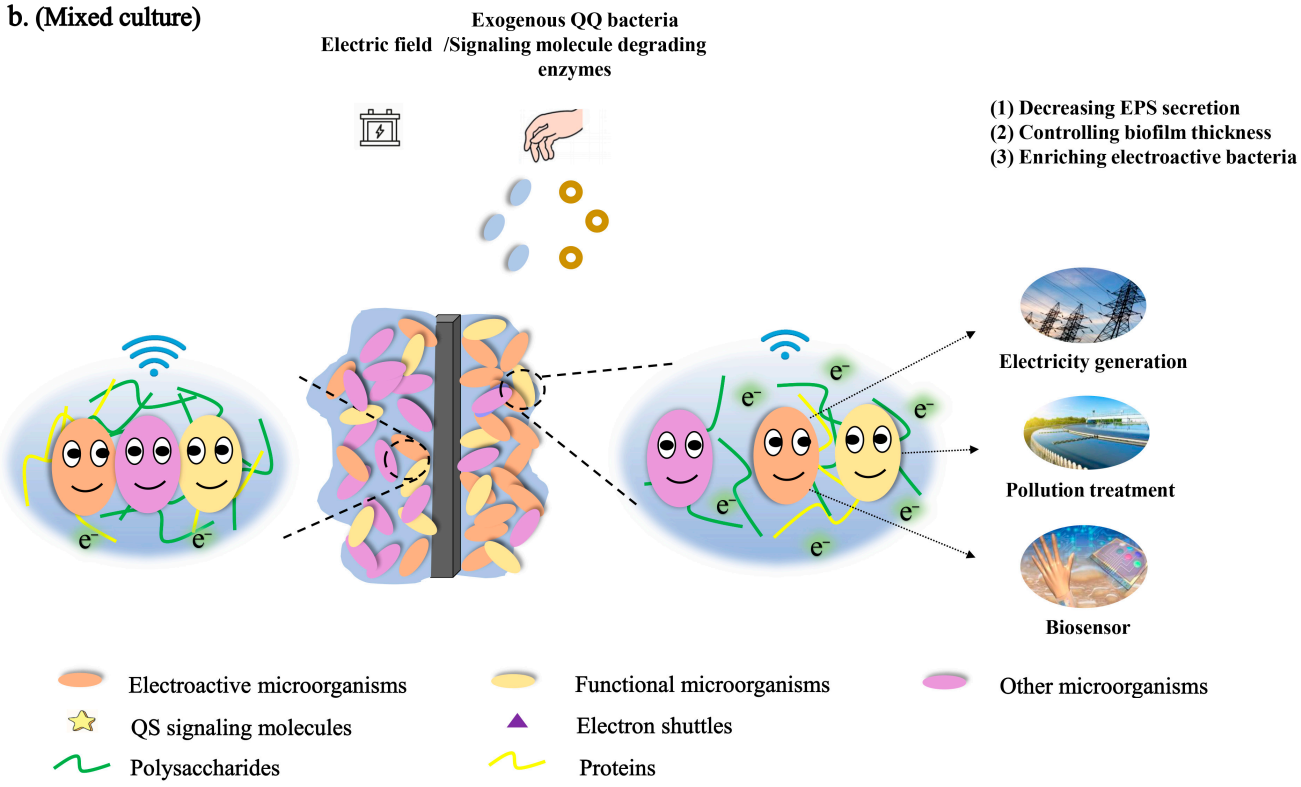

Figure 2. Schematic diagram of QS regulation for electrode biofilms in BESs: (**a1**) Pure culture of QS enhancement; (**a2**) Mixed culture of QS enhancement and (**b**) QS inhibition.

4.1. Hydrogen Production

The QS regulatory mechanism has been widely applied to enhance the energy recovery of BES [104]. Cai et al. [83] added short-chain AHL (3OC6-HSL) to a single-chamber mixed-culture MEC to improve the hydrogen generation rate, which increased by 5.57%, 38.68%, and 81.82% under different applied Voltages of 0.8, 0.6, and 0.4 V, respectively. The research shows that the addition of AHL altered the microbial community structure of the anode and cathode biofilms, resulting in more electroactive bacteria and fewer hydrogenophiles (such as methanogens and acetic acid-producing bacteria). Similarly, Liu et al. [105] added 3OC6-HSL as a signaling molecule during the first three cycles of biofilm domestication into a single-chamber MEC. After the MEC start-up, the hydrogen yield in the AHL group remained stable at 1.42 $\pm$ 0.05 mL/mg COD, which was 32.7% higher than that in the control group (1.07 $\pm$ 0.07 mL/mg COD). This increase in hydrogen generation rate may be attributed to the enhanced and efficient transfer of extracellular electrons (generated by consuming acetic acid) from microbial cells to electrodes, facilitated by the addition of 3OC6-HSL.

4.2. Electricity Generation

Both endogenous and exogenous AHLs can enhance the electrochemical activity of MFC mixed-culture bioanodes. Endogenous AHLs increased the energy recovery rate of MFCs by 38.0% and shortened the start-up period by three days. However, exogenous AHL (3OC12 HSL) increased the energy recovery rate of MFCs by 76.6%, shortened the start-up period by nine days, and increased the relative abundance of *Geobacter* from 56% to 71–78%. The research shows that both endogenous and exogenous AHLs improved some intrinsic characteristics of biofilms, such as biomass, density, and cell Viability, while increasing the concentration and redox activity of EPS [45]. Christwaldana et al. [106] fixed QS signaling molecules (phenylethanol and tryptophan) secreted by yeast on an MFC carbon felt anode for surface chemical modification to enhance yeast biofilm formation and electrical activity. The results show that the MFC immobilized with phenylethanol and tryptophan had similar

MPDs (159.46 ± 10.68 and 156.57 ± 5.84 mW/m^2), which were 10.5% and 8.5% higher than the control group, respectively. This is because the electrode modified with phenylethanol and tryptophan reduced the internal resistance of charge transfer, promoted electron transfer, and maintained high current generation. The addition of 100 nM quinolone to MFC using the extreme microbial *Halanaerobium praevalens* as an anode-producing bacterium enhanced the formation of anode biofilms, resulting in a 30% increase in cell energy density [107]. Hu et al. [108] constructed an AND logic gate based on a synthetic QS module in the mtrA knockout mutant of *S. oneidensis* MR-1, which is a genetically engineered bacterium containing isopropyl groups β-D-galactopyranoside (IPTG) controlled Ptac promoter and Ptac controlled LuxR (QS signal regulator). This AND logic gate structure allows AHL (3OC6-HSL, 10 nM) and IPTG (0.01 mM) to regulate the generation of current when they exist in the MFC anode chamber, resulting in an MPD of 10.33 ± 1.33 mW/m^2, which is four times higher than the control group (2.31 ± 0.42 mW/m^2). Li et al. [109] designed a population-state decision (PSD) system based on QS that can autonomously transition the main metabolic flux from the initial microbial growth mode to the enhanced EET mode after reaching a certain population-state threshold. In *S. oneidensis* MR-1, an artificial AND gate was constructed with *lux*R and *lux*I. The superfolder green fluorescent protein (sfGFP) reporter was driven by a responsive PLUX promoter to facilitate the output measurement. The results show that the fluorescence of sfGFP increased with an increase in 3OC6-HSL concentration (0.024 to 100 nM), and this AHL-dependent system output indicates that the AHL level can reflect the state of the microbial population. Three modules A, B, and C, corresponding to the Mtr catheter OmcA-MtrCAB, tetraheme methylnaphthol dehydrogenase Cyma, and electron shuttle flavin synthesis pathway, respectively, with good EET enhancement performance through intelligent regulation, were reprogrammed and assembled into an EET network. The maximum current density obtained reached 783 mA/m^2, 4.8 times higher than that of the control group.

4.3. Chemical Synthesis

C6-HSL, as a typical QS signaling molecule, can be used to regulate the formation of dual-chamber MES cathode biofilms by adding 50 μM C6-HSL to the MES cathode during the 430–860 h operation period, followed by three cycles (860–1300 h) without the addition of C6-HSL. This resulted in a 94.8% increase in acetic acid production compared to the control group. The research shows that the increase in exogenous C6-HSL could promote the electron transfer pathway related to nicotinamide adenine dinucleotide dehydrogenase, coenzyme Q, and proton power. The removal of AHL will not immediately affect EAB but will help to improve some internal characteristics of the biofilms, such as biomass, density, and cell activity. Additionally, the proportion of hydrogen generation bacteria in the cathode microbial community increases, promoting the reduction of CO_2 to acetate through H_2 mediation [72]. Adding C8-HSL (10 μM) to the dual-chamber MES cathode can promote the synthesis of long-chain fatty acids, resulting in a 61.48% increase in the concentration of hexanoic acid compared to the control group. The research shows that adding AHL could increase the adhesion of electrode microorganisms and the proportion of live cells, thereby enhancing the electrochemical activity of EAB. It could also stimulate the enrichment of chain elongation microorganisms, regulate CoA transferase activity, amino acid synthesis, and carbon metabolism, and promote chain elongation metabolism [11].

4.4. Pollution Treatment

Borea et al. [110] studied the effect of an electric field (current density: 0.5 mA/cm, 5 min on/20 min off) on the removal of QS and emerging pollutants based on eMBR. Compared to MBR, they achieved a significant reduction in C8-HSL (~76.3%) in eMBR, thereby reducing the concentration of membrane fouling precursors (EPS) and transparent exopolymer particles. The research shows that signaling molecules enabled bacteria to express genes with biological fouling and EPS secretion phenotypes. As C8-HSL controls the activation of genes related to membrane biological fouling, reducing its concentration

also decreases the concentration of membrane fouling precursors. In addition, eMBR was found to effectively remove atrazine (ATZ) and estrone (E1), with a 36% increase in the removal rate. The QQ bacteria *Rhodococcus* sp. BH4 can significantly promote the removal of total organic carbon (TOC) using MFC mixed culture bioanodes. The highest removal rate of TOC was achieved by adding 40 mg BH4 to the double-chamber MFC anode (73%), which was 23% higher than that of the control group. This research shows that BH4 could successfully control the anode biofilm thickness of MFC by inhibiting QS between anode bacteria [46]. In addition, AHLs contained in sludge EPS can significantly promote the tolerance and degradation of MFC mixed culture bioanodes to chloramphenicol (CAP), and different AHLs distributed in different spaces within sludge EPS have different QS regulation effects. The AHLs in sludge tightly bound-EPS (TB-EPS) showed the most significant promotion effect, and MFC with exogenous TB-EPS exhibited a 2.03 times higher CAP removal rate than that in MFC with TB-EPS extracted AHLs. The research shows that AHLs significantly activate the biochemical metabolism and QS functional activity of biofilms during the early stages of domestication. This enabled microbial self-assembly to form electrode biofilms with excellent physicochemical properties (three-dimensional porous membrane structure, high biomass, strong cell activity, high ratio of proteins, and conductive substances in biofilms EPS) and stable microbial ecological structure (rich biodiversity, uniform proportion of functional microbiota, enrichment of bifunctional microbiota, and strong positive interaction of microbiota) [10].

4.5. Biosensor

Compared to traditional sensors, electrochemical biosensors, particularly MFC-based biosensors, have received widespread attention due to their stable performance, high sensitivity, and ease of use [111]. In MFC biosensors, biological anodes are typically used as sensing elements for monitoring toxicity levels [112]. Pan et al. [113] found that adding two types of AHLs (C6-HSL and 3OC12-HSL) to a single-chamber heavy-metal toxicity sensor MFC significantly increased the ratio of active cells and *Geobacter* in the anode mixed electrode biofilms, thus expanding the linear sensing range of MFC for Pb^{2+} and enhancing the ability of electrode biofilms to recover electricity after being subjected to high concentrations of Cu^{2+} toxicity. Chung et al. [114] added acylase (5 μg/L), which led to a Very low detection limit of naphthenic acid and a quantitative determination of naphthenic acid concentration (9.4–94 mg/L). Compared to the control group, the sensitivity of the biosensor and the electrical signal output increased by 40% and ~70%, respectively. The study shows that the addition of acylase increased the expression of QS-related genes (*lasR*, *lasI*, *rhlR*, *rhlI*, *lasA*, and *luxR*) by 7–100% the abundance of electroactive bacteria in *Geobacter* (from 42% to 47%) and *Desulfovibrio* (from 6% to 11%). Acylase, a degrading enzyme of AHL, is generally used to inhibit QS. However, Pan et al. [113] also found that the addition of acylase can reduce the detection linearity and toxicity shock resistance of the single-chamber heavy-metal toxicity sensor MFC, which contradicts the research results of Chung et al. [114]. Therefore, further research is needed to clarify the effectiveness of acylase on biosensors.

Table 3. Application of QS regulation for electrode biofilms in bioelectrochemical systems.

Application	Additive	Additive Amount	Bioreactor/Microorganisms	Performance Impact	Reference
Hydrogen production	3OC6-HSL	10 mM	Single chamber MEC/Mixed culture	Hydrogen production increased by 5.57%, 38.68%, and 81.82% with applied Voltages of 0.8 V, 0.6 V, and 0.4 V, respectively.	[83]
	3OC6-HSL	10 μM	Single chamber MEC/Mixed culture	Hydrogen production increased by 32.7%.	[105]

Table 3. *Cont.*

Application	Additive	Additive Amount	Bioreactor/Microorganisms	Performance Impact	Reference
Electricity generation	3OC12-HSL	10 μM	Dual chamber MFC/Mixed culture	Energy recovery efficiency improved by 76.6% and start-up time was reduced by 9 days.	[45]
	Phenylethanol and tryptophan (modified to anode electrode)	10 μM	Single chamber MFC/Brewing yeast	MPD increased by 10.5% and 8.5%, respectively.	[106]
	Quinolone	100 nM	Single chamber MFC/*H. praevalens*	Energy density increased by 30%.	[107]
	3OC6-HSL	10 nM	Dual chamber MFC/*S. oneidensis* MR-1	MPD increased by four times.	[108]
	3OC6-HSL	100 nM	Single chamber MEC/*S. oneidensis* MR-1	EET enhanced by 4.8 times.	[109]
Chemical synthesis	C6-HSL	50 μM	Dual chamber MEC/Mixed culture	Acetic acid production increased by 94.8%.	[72]
	C8-HSL	10 μM	Dual chamber MEC/Mixed culture	Caproic acid concentration increased by 61.48%.	[11]
Pollution treatment	Electric field	0.5 mA/cm (5 min on/20 min off)	eMBR/Mixed culture	Decreasing 76.3% of C8-HSL, 78.1% of the protein content in EPS, and 47.11% of TEP; ATZ and E1 efficiency increased by 36%.	[110]
	Rhodococcus sp. BH4	40 mg	Dual chamber MFC/Mixed culture	TOC removal efficiency increased by 23%.	[46]
	Sludge EPS (containing C7-HSL, 3OC6-HSL, C4-HSL, and 3OC8-HSL)	EPS extracted from 23 mL of sludge	Dual chamber MFC/Mixed culture	CAP removal rate increased by 2.03 times.	[10]
Biosensor	C6-HSL and 3OC12-HSL	10 μM	Single chamber MFC/Mixed culture	Sensitivity improved by 2.57 and 1.92 times, respectively; Voltage recovery was about 62% under 10 mg/L Cu^{2+}.	[113]
	Acylase	5 μg/L	Dual chamber MXC/Mixed culture	Sensitivity improved by 40% and current output increased by 70%.	[114]

5. Conclusions and Perspectives

The important role of QS systems in improving EET, biofilm formation, and pollutant tolerance and degradation has attracted increasing attention. However, QS regulation for electrode biofilms in BESs is still in its early stages. Existing studies on QS regulation for mixed-culture electrode biofilms are mostly conducted through the random addition of different types of AHLs (G^-), lacking targeting and accuracy. Since G^- and G^+ bacteria normally coexist in mixed-culture electrode biofilms, studies on QS regulation by adding AIPs (G^+) and AI-2 (G^- and G^+) are still limited. Furthermore, the effects and functional mechanisms of endogenous AHLs on the formation of mixed-culture electrode biofilms remain unclear, necessitating systematic exploration. Moreover, studies on QS regulation for pure-culture electrode biofilms mainly focus on classic electroactive strains, such as *Geobacter* sp., *Shewanella* sp., and *Pseudomonas* sp. Other electroactive strains still need to be investigated. With the aid of synthetic biology methods, indirect or DET between biofilms and electrodes can be further improved based on QS regulation in the future. In addition, the QS regulation for electrode biofilm formation is a complicated process that likely involves a balance between QS and QQ, which requires a deep understanding of the QS and QQ mechanisms. Therefore, investigating QS regulation mechanisms and

strategies for electrode biofilms will open new avenues for improving BES performance and expanding their applications in bioenergy production, waste treatment, chemical synthesis, and biosensors.

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