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PERSPECTIVE

Integrated energy view of wastewater treatment: A potential of electrochemical biodegradation

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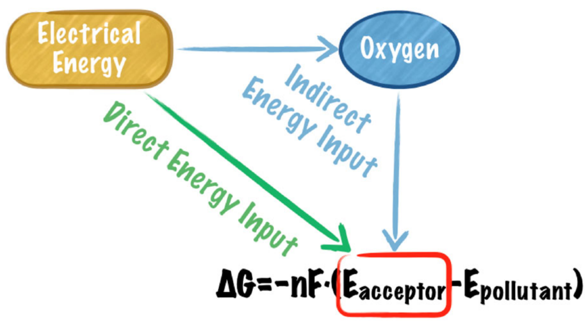
HIGHLIGHTS

- Energy is needed to accelerate the biological wastewater treatment.
- Electrical energy input in traditional technology is indirect and inefficient.
- Direct injection of electricity can be a game changer to maximize energy efficiency.
- Microbial electrochemical unit for decentralized wastewater treatment is proposed.

GRAPHIC ABSTRACT



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ABSTRACT

It has been more than one century since the activated sludge process was invented. Despite its proven stability and reliability, the energy (especially the electrical energy) use in wastewater treatment should evolve to meet the increasingly urgent demand of energy efficiency. This paper discusses how the energy utilized in conventional biological wastewater treatment can be altered by switching the indirect energy input to a direct electricity injection, which is achieved by the electrode integration providing extra thermodynamic driving force to biodegradation. By using electrodes instead of oxygen as terminal electron acceptors, the electrical energy can be utilized more efficiently, and the key of direct use of electrical energy in biodegradation is the development of highly active electroactive biofilm and the increase of electron transfer between microbes and the electrode. Furthermore, the synergy of different microbial electrochemical units has additional benefit in energy and resource recovery, making wastewater treatment more sustainable.

The biological unit is the most widely used in current wastewater treatment plants (WWTP) because of its advantages of sustainability and cost performance. The activated sludge process has been born for more than 100 years and still a successful technology to date across the globe (van Loosdrecht and Brdjanovic, 2014). Given the rapid increase of WWTPs as the population growing, this industry consumes up to ~3% of global electricity generation (Li et al., 2015). Decentralized treatment is considered as one solution to minimize energy consumption by avoiding large water transportation (Ren and Umble, 2016). From the energy point of view, biological treatment is still necessary in decentralized units considering its relatively low energy need. In my opinion, the key to maximizing energy efficiency in such system is to fundamentally optimize the energy flow.

For the typical activated sludge treatment, about half of the electrical energy is consumed by air demand (McCarty et al., 2011). Assuming that all electrical energy is fully used to generate bubbles through diffuser and oxygen completely dissolves without any loss, only 21% of the gas

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pumped to water is oxygen. Given the electrical energy utilized to pump air into wastewater as 100%, therefore the part for oxygen supply can not exceed 21%. The actual efficiency will further decrease when mass transfer, mechanical and frictional losses are considered. This inefficient aeration is widely used in WWTPs because it is relatively easy to apply in large scale and the total cost is balanced by scale effect. However, in decentralized units, the energy efficiency rather than scalability should be emphasized.

The essence of energy use in biodegradation is the electron transfer reaction. With a proper electron acceptor, the energy conserved in pollutants can be released to support biological activities, according to Eq. (1):

$$\Delta G = -n\Delta EF, \quad (1)$$

where n denotes the transferred electron number, ΔE the potential difference between electron acceptor and donor and F the Faraday's constant. Therefore, the key to optimize the energy efficiency is to maximize the potential gap between donor and acceptor (ΔE). Looking specifically at aeration in activated sludge process, oxygen is supplied as a high-potential electron acceptor, which can be considered as an indirect energy input (blue pathway in Fig. 1(a)).

Recently, the rapid progress of microbial electrochemical technology (MET) (Logan and Rabaey, 2012) arises a new question. If the aim of energy input is to provide electron acceptors to complete the oxidation, why do not use electrodes as a potential-variable acceptor instead of oxygen? The green pathway in Fig. 1(a) illustrates a direct utilization of energy for electron acceptor supply. As an electron acceptor, electrode is different from oxygen, which is not chemically involved in reaction, but merely harvests electrons. In potential-adjustable METs, such as microbial electrolysis cells (MEC), potential is a crucial parameter to regulate the system performance. With a small amount of electrical energy added (~0.5 V of bias voltage), electrons from the degradation can be deposited to protons, forming H_2 on the other electrode. In this process, energy is directly injected to facilitate degradation, and recovered with the pollutant chemical energy, simultaneously recovering resources such as active nitrogen and phosphate (Chen et al., 2017; Li et al., 2020).

Toward the ideal pathway discussed above, the biggest

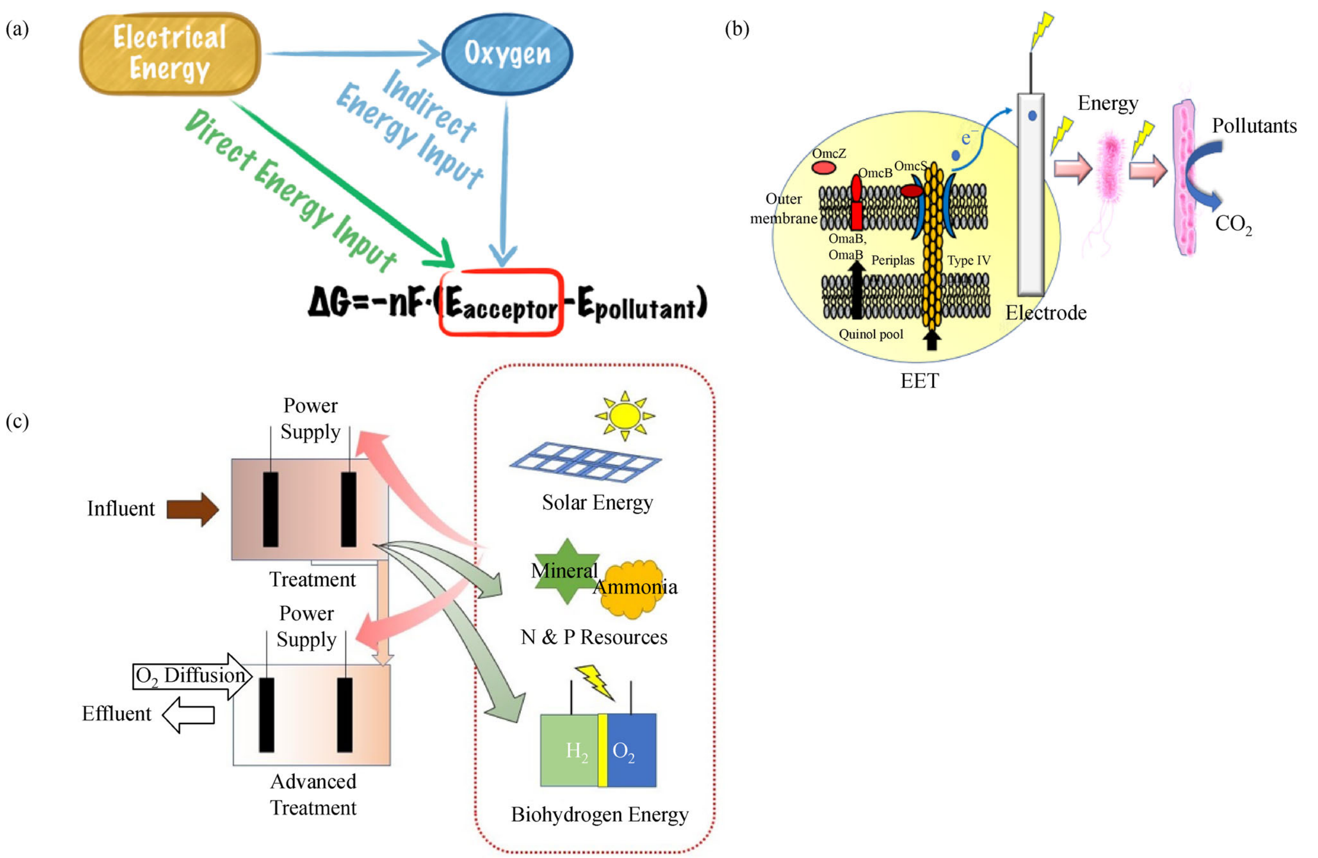

Fig. 1 (a) The integrated energy view in biological wastewater treatment. $E_{acceptor}$ and $E_{pollutant}$ are redox potentials of the electron acceptors and electron donors (most organic pollutants are electron donors). The blue and green pathways show the indirect and direct energy inputs. (b) The direct electrical energy injection through extracellular electron transfer (EET). (c) Sketch of METs for decentralized wastewater treatment. The pink arrows represent energy consumption, and green arrows represent H_2 energy recovery.

challenge would be the electron transfer across microbial cell membranes. They are mainly composed of a lipid bilayer and mobile proteins and generally considered insulative, except for electroactive bacteria, who directly exchanges electrons with solid electrodes. Electrons can be transported through cytochromes associated with cell membrane, electron shuttles or even conductive appendages like e-pili (Shi et al., 2016). These microbes are widely found in wastewater and can be easily acclimated, paving a way for electrical energy injection (Fig. 1(b)). Since the acceptor in such reaction is actually the electrode, it is possible to control the energy to microbes simply by regulating the applied potential. From the perspective of kinetics, Gibbs free energy of electrode respiration participates in the electron allocation between cell synthesis and electron transfer reaction, therefore it is also possible to influence metabolic rate with injected energy (Wilson and Kim, 2016; Rittmann and McCarty, 2001). Electroactive bacteria are also able to form a mutualism with fermenting microbes to degrade complex pollutants such as propionate, cellulose, and actual wastewaters (Yan and Wang, 2019). Conductive e-pili was recently found in *Syntrophus aciditrophicus*, a model hydrogen donating syntroph (Walker et al., 2020). This finding indicates a surprisingly ubiquitous existence of direct interspecies electron transfer (DIET), and a potential of sharing energy to broader population of microorganisms. Therefore, higher reaction rates could be achieved not only on electrode surface, but also eventually, the degradation.

To meet the requirement of water reuse, a two-stage system including MET and advanced treatment units is proposed. Energy conserved in organic pollutants is extracted by METs to generate cathodic hydrogen, which is collected to fuel cells generating electricity back for use. Additionally, solar panels are designed to produce green electricity as an energy source. For example, at the hydrolyzation period, electrochemical biodegradation unit stimulates the decomposition of organics and then refractory pollutants are reduced in the advanced treatment unit (Fig. 1(c)). Oxygen is transported through passive diffusion to the cathode, where all residue organic pollutants are degraded effectively while synthesizing H_2O_2 for disinfection (Zhao et al., 2021). The key to this system is the large electrode-biofilm interface for energy delivery and the highly efficient interspecies electron transfer, which can be improved based on the understanding of biofilm and micro-niche on electrode (Yan et al., 2020). Compared to the conventional activated sludge process, this approach is more efficient in energy consumption as previously discussed, and also saved the treatment of excess sludge. More importantly, it provides us additional parameters (voltage, current, etc.) to precisely manipulate the complex biological process, which can be a window to apply artificial intelligence in wastewater treatment in the future. However, this system is biofilm dependent, which is limited by the ratio of area of electroactive biofilm to total volume, associated with the total cost of electrode materials. Thus, a cost-benefit analysis has to be performed according to specific cases.

Overall, MET provides a more efficient alternative to aeration in conventional biodegradation, and the relatively small size of decentralized wastewater treatment units facilitates electrode in a whole size. With the fast progress of bioelectrochemical studies, this new system would contribute to a more sustainable future for WWTPs.

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