Perspective

Bioelectrochemistry for flexible control of biological processes

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Societal awareness and worries about the future of the earth are rapidly increasing. Who does not want to contribute to a sustainable future, in which the earth’s resources will still be available for future generations?

In my view, a sustainable world is a world in which we live in close collaboration with nature. In nature, microorganisms are a key player in the global carbon, nitrogen and phosphorous cycle. Therefore, these natural processes are the key to sustainable solutions for environmental problems, like the recovery of resources from waste streams, sustainable energy generation, and degradation of pollution. The main challenge of these biological conversions is to engineer them towards the desired rate and efficiency, to obtain a sustainable and effective technology.

Currently, biotechnological processes are widely applied in wastewater and gas treatment for removal and recovery of organic material, nitrogen, phosphate and sulphur. All these biological conversions consist of combinations of reduction and oxidation reactions. Measurement of Oxidation-Reduction Potential (ORP) that reflects the availability of electron donors and acceptors in solution is used as an operational parameter for steering selectivity and stability of these biological processes. Each process has its own ORP range, in which the conversion is most effective (Table 1) [1].

Supply of electron donor and acceptor is the common strategy to control the redox potential. For example, to remove organic carbon from wastewater, the supply of air is controlled to keep the desired ORP. Based on ORP measurements alone, however, it is challenging to precisely control the biological conversions, particularly when specific performance is needed. The reason is that ORP is a lumped parameter that reflects the presence of all oxidizing and reducing components in the environment. As a result, ORP based control does not always result in high selectivity of biological conversions. In addition, the potential range in which redox conditions can be tuned with ORP is limited.

To overcome the challenge that electron donor and/or acceptor are often limiting biological conversions, electrodes can be used as an additional source or sink for electrons. Electrodes can be used to increase the operating range of biological conversions because the electrode potential can be precisely controlled at any oxidizing or reducing condition. As many different bacteria can exchange electrons with an electrode [2–4] — so-called electroactive bacteria — electrodes provide a unique platform for the study and control of microbial conversions. These electroactive bacteria commonly live in biofilms that are attached to the electrode. This interaction between electrodes and bacteria forms the basis of Microbial Electrochemical Technologies (METs) [5,6].

In the early 2000s, the first principles of Microbial Fuel Cells (MFCs) were demonstrated [7]. In the following decade, METs have gained much attention as a new, sustainable technology to convert chemical energy into electrical energy or vice versa. Potential applications are the recovery of energy and nutrients from wastewater, and the conversion of electricity into fuels and chemicals [6]. It was, for example, discovered that bacteria could take up electrons (or reducing equivalents in the form of hydrogen) from a cathode [8], thereby reducing CO₂ to products like methane [9,10], acetate [11], and medium-chain fatty acids [12,13]. This discovery opened new opportunities for the conversion of electricity and CO₂ into added-value components using microorganisms.

In the coming decades, many new applications will arise that are based on the exchange of electrons between microorganisms and electrodes, both from a control and a sustainability perspective. One important reason that electrodes will play a more dominant role in our society in the future is the rapidly developing energy transition. As we will become more and more reliant on renewable electricity in our energy mix, processes that can exchange electrical energy for chemical energy in an efficient way will become more important. A setback of many electrochemical processes today is that they are not truly sustainable, since they require scarce and expensive catalysts, and they do not occur at ambient conditions. This is where electroactive microorganisms come in – they are the potentially more sustainable alternative.

So what will biological processes and electrochemistry in 2050 look like? And what is needed to get there?

In 2050, many biological processes, for example, for organic matter and nutrient removal, will not rely anymore on aeration. Electrodes will have taken over the role of oxygen as an electron acceptor. Biological desulphurization is one of those processes where aeration could be replaced by electrodes: we have recently shown that aerobic sulphide oxidizing bacteria can remove sulphide from solution under anaerobic conditions, and can shuttle the electrons to an electrode in an
Table 1
Overview of the ORP range in which different biological processes typically occur.

| Biochemical Activity       | ORP Range (mV) |
|---------------------------|----------------|
| Aerobic carbon oxidation  | +50 to +200    |
| Nitrification             | +150 to +350   |
| Denitrification           | −50 to +50     |
| Acidification             | −200 to −40    |
| Sulphate reduction        | −250 to −50    |
| Methanogenesis            | −400 to −200   |

In conclusion, electrodes offer many exciting opportunities for a new, flexible way to control biological conversions. Many scientific and engineering challenges remain. The high versatility of reactions and applications is the key to success of METs: niches need to be identified where METs will indeed be a more sustainable and economically alternative to conventional (bio)processes. I am excited to further contribute in this field of METs with research, scaling-up and pilot testing, to contribute to a more sustainable world.

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