Editorial

Bioelectrochemical Systems and Applications—Taking A Broader Perspective and Highlighting Relevance to the Circular Economy

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1. Introduction

As the push towards circular economy continues to gain momentum, the demand for scientific innovations will undoubtedly be a key driver in any effort made to realise the full potential of this new approach to global economy. The aim of a circular economy, in contrast to the wasteful practices of the current linear economy, is to ensure significant waste reduction and minimisation or elimination of resource depletion [1,2]. This can be accomplished by putting more strategic efforts on the sustainable reuse, repurpose, recycle, remanufacture, reduce and recover of all materials. Recent and emerging advances in some scientific fields have already demonstrated that such a goal is achievable. One of those fields which is the focus of this journal is in the development and utilization of bioelectrochemical systems which originated as microbial fuel cell in 1993 [3], but have undergone considerable improvements in recent years due to the increasing impact of new developments in microbiology, material science, nanotechnology and engineering, as well as increasing multidisciplinary collaborations.

Bioelectrochemical systems (BES) are innovative and unique in their integration of biological and electrochemical processes to purposefully generate novel and effective solutions for key important issues that are critical for achieving circular economy and meeting the green chemistry principles [1,2]. Although the term bioelectrochemical systems has largely been used in reference to some aspects of the technology, it is much broader than that and it is important to recognise the full breadth of the technology. BES encompasses various innovative systems and applications that integrate biological and electrochemical processes to achieve the production of sustainable energy, remediation of the environment, recovery of valuable resources from waste streams, and the development of highly sensitive and selective analytical technologies for environmental monitoring, medical diagnosis and food safety assessments [4–8].

The new journal, "*Bioelectrochemical Systems and Applications*", therefore aims to provide a key platform and conduit for the dissemination of innovative research, theoretical insights, and experimental findings that are derived from the integration of biological and electrochemical processes for solving key issues of global concern and that can make significant contribution to the circular economy. The diverse range of systems that have been developed by the integration of these processes include biosensors, enzyme-based and microbial fuel cells, microbial electrolysis cells, and much more that will be discussed later. In this editorial, the multidimensional nature, emerging technologies, interdisciplinary frontiers, diverse applications, future directions and challenges of bioelectrochemical systems is summarised to highlight the focus areas of this journal and the full breadth of BES.

2. The Multidimensional Modes of Bioelectrochemical Systems

The versatility of BES is reflected by the wide range of systems that integrate biological components, such as enzymes, DNA, aptamers, antigens/antibodies, whole cells and microorganisms, with the relevant electrochemical processes to provide novel solutions to various problems [4–8]. The resulting systems offer unique advantages and applications that are important for energy production, waste reduction and management, generating or recovering valuable chemical and biological products, and developing advanced sensing and environmental technologies.

2.1. Biosensors

By any measure, one of the most recognised, successful and commercially available applications of BES are biosensors [7,8]. Typically, they are constructed by integrating biological recognition elements, such as enzymes, DNA, aptamers, antibodies/antigens, microorganisms and whole cells, with electrochemical transducers to achieve highly sensitive and selective detection of a wide range of organic and inorganic analytes. The first biosensor was developed by Leland C. Clark, Jr in 1956 by using an oxygen electrode to create a glucose biosensor. Significant improvement in biosensor performance has been realised since then and, in particular, in recent times by incorporation of various nanomaterials into these devices, as well as through availability of new surface modification techniques [7,8]. These recent developments have led to ultrasensitive detection of food contaminants, environmental pollutants, pathogens and clinically important biomarkers. The availability of biosensors has, in particular, been highly beneficial for clinical diagnosis and improving patient care.

2.2. Biofuel Cells

In the quests to reduce the impact of waste streams on the environment, various enzymatic biofuel and microbial fuel cells have been developed to mitigate this problem via generation of useful electrical energy from these streams [4–6,9]. This is accomplished in enzymatic biofuel cells by using specific enzymes to catalyze the oxidation of organic materials in the waste streams. On the other hand, the metabolic processes of microorganisms are used in microbial fuel cells to convert organic substrates into electrical energy. These biofuel cells are therefore reliable renewable energy sources with the advantage of reduced greenhouse gas emissions. The improvement of the longevity and performance of these systems by scaling up and incorporation of various nanomaterials are the current focus of numerous research activities in this area [5,9].

2.3. Microbial Electrolysis Cells

As an anaerobic biological system, microbial electrolysis cells (MEC) utilize the application of small voltage together with microbial catalysis to initiate the electrolysis of water [5]. Thus, providing an innovative and renewable route for hydrogen generation. Other resources that can be recovered by MECs include alcohols, hydrogen peroxide, methane and organic acids. In effect, MEC is capable of simultaneously achieving waste treatment, clean energy production and other resource recovery [5]. These are desirable abilities that are in accord with the principles of a circular economy. However, further development of MEC is still required to achieve a reliable commercial scale resource recovery. Various efforts made towards achieving this goal include the investigation of different cathode catalysts and improvement of electron transfer and product yield [5].

3. Emerging Technologies

3.1. Biocapacitors and Energy Storage

Biocapacitors are part of a class of bioelectronic devices which include biosensors, bioelectronic circuitry, and biofuel cells. They are fabricated from redox proteins, enzymes, organelles and whole living cells. The biomaterials are used as the capacitive elements for charge storage based on the utilization of their redox-active components [10,11]. Thus, this is one of the exciting frontiers in BES research which combines biological energy conversion with capacitive storage to achieve a novel bioelectricity storage from the electrical energy generated from biological reactions. Although the research in biocapacitors is still in early stages, some of the applications that will benefit from its fully functioning development are wearable electronics and self-powered biosensors [5,10,11].

3.2. Microbial Desalination Cells

One of the frontiers in the application of BES is Microbial Desalination Cells (MDC) which addresses the two-fold issue of water scarcity and energy demand [5,9,12,13]. MDC achieves desalination by utilizing the potential gradient produced from the organic substrate oxidation by anodic bacteria to incite migration of ions. It can simultaneously carry out wastewater treatment, saline water desalination, and electricity generation. These are achieved by using microbial activity to desalinate water, while also generating electricity. Thus, MDC offer a solution to two significant challenges simultaneously. The improvement of the performance of MDCs by scaling up and achieving increased practical efficiency are the focus of on-going research [5,9,12,13].

3.3. Bioelectrosynthesis Systems

The ability of enzyme-based and microbial-based bioelectrosynthesis systems to produce valuable chemicals and fuels has gained considerable interest [5]. Bioelectrosynthesis systems utilize extracellular electron transport pathways to enhance cellular metabolism [14]. The synthesis of complex organic molecules in these systems are driven by electrochemical energy, while employing the microorganisms or enzymes as the biocatalysts to accelerate the processes. The use bioelectrosynthesis systems offers sustainable routes for chemical production which can improve the economic viability of bio-based syntheses, particularly for petrochemical-based syntheses [14]. This approach therefore conforms with both the green chemistry and circular economy principles [5,14].

4. Interdisciplinary Advances

4.1. Electrochemical Controlled Bioreactors

A relatively recent advancement in bioprocess engineering involves the integration of electrochemical control mechanisms in bioreactors to enable precise control over redox conditions. This has been found to be particularly useful for simultaneous improvement in pollutant removal and hydraulic performance of membrane bioreactors [15]. The integration of an electrochemical process often results in the enhancement of the bioproduction process efficiency and selectivity. The production of high-value biochemicals and pharmaceuticals is likely to benefit from the incorporation of an electrochemical process. Also, considerable removal of phosphorus and micropollutants can be achieved with electrochemical membrane bioreactors [15].

4.2. Photo-Bioelectrochemical Cells

Another significant advancement is the development of photo-bioelectrochemical cells through the integration of BES with photosynthetic processes [5,16]. These systems utilize the photosynthetic conversion efficiencies of bacteria and algae to simultaneously achieve wastewater treatment and generate power. In these cells, the bioelectrochemical processes are driven by the harnessed light energy. Thus, making solar energy conversion and sustainable fuel production possible. The performance of these cells has been improved significantly by the recent improvements in electrode materials and biofilm engineering [5,16]. The ability of photo-bioelectrochemical cells to achieve both wastewater treatment and generate power is also in accord with the principles of green chemistry and circular economy. Furthermore, these systems can make significant contributions in addressing climate change and energy shortage through adoption for carbon capture and biodiesel production, respectively [5,16].

4.3. Electrochemical Bioremediation Systems

These systems are designed to utilize innovative approach to achieve environmental clean-up and waste management. The breakdown of pollutants in waste streams by microorganisms is substantially enhanced in these systems by utilizing various electrochemical processes [5]. Electroactive microbes in the anodic chamber are utilized in microbial remediation systems to oxidize pollutants completely or into less toxic forms. In contrast, the cathode in these systems performs as an electron donor to achieve the reduction of the pollutants [5]. The highly efficient performance and the ability to simultaneously produce energy and recover heavy metals with electrochemical bioremediation systems offer great promise for contributing to circular economy where contaminated waters require adequate treatment and provide opportunity for resource recovery.

4.4. Bioelectronic Interfaces

Bioelectronic interfaces are another recent advancement in BES research where direct communication is achieved between biological entities and electronic devices. Various advanced bioelectronic devices, neural interfaces, and novel approaches in synthetic biology can be developed through these interfaces. The ability to achieve more efficient and biocompatible interfaces will benefit from the new developments in materials science, nanotechnology and engineering [5,17,18]. These interfaces are particularly useful for interfacing with biological systems for electrophysiology, biochemical sensing, point-of-care diagnostics, wearable and implantable technologies, and in organ-on-chip systems [18]. One area where these interfaces can have significant impact is in its application as a novel replacement for electronic-based pharmaceutical intervention used for direct stimulation of the nervous system [17]. The advantages that can be realised from the use of bioelectronics include time specificity, method, treatment location, ability to refine and update therapy algorithms in software iteratively [17]. However, the invasiveness of surgical implantation of the device is a noted disadvantage that requires further improvement.

5. Applications of Bioelectrochemical Systems

As already demonstrated, BES has been successfully used in wide ranging applications. Some broad examples in addition to those already discussed are:

5.1. Treatment of Waste Streams

Microbial fuel cells and microbial electrolysis cells can be used simultaneously to treat wastewater and generate electricity or hydrogen. These bioelectrochemical systems are therefore undoubtedly suited for achieving a sustainable waste management with the benefit of recovering valuable resources [5,9]. The ability to achieve both effective waste treatment and resource recovery is clearly in accord with the principles of a circular economy.

5.2. Production of Renewable Energy

Increasingly, renewable energy technologies utilising biofuel cells and bioelectrosynthesis systems are having significant impact in the effort to shift globally towards renewable energy. These systems readily convert organic matter into electricity to provide alternative energy sources, hydrogen, or other fuels.

5.3. Bioremediation

Various environmental pollution issues are being addressed through the development of BES-based bioremediation systems. These systems utilize electrochemical processes to accelerate breakdown of contaminants. As previously outlined in Section 4.3, these systems enable a more efficient, rapid and controlled approach to pollutant clean-up and minimisation [5].

5.4. Recovery of Valuable Resources

The recovery of valuable resources, such as metals and nutrients, from waste streams has also attracted considerable interest in the application of BES. This application is aimed at transforming wastes into valuable products, as discussed in Section 4, which is in accord with the principles of the circular economy [1,2].

5.5. Sensitive and Selective Sensing Devices

The detection and quantification of various organic and inorganic analytes has been revolutionized over the past four decades through the development of various electrochemical biosensors and immunoassays [7,8]. These devices which contain at least one biomolecule operate with an electrochemical transducer to enable highly selective and ultrasensitive detection of a wide range of analytes and have enabled considerable applications in environmental monitoring, food safety assessment and for clinical/medical diagnosis.

6. Future Considerations

Bioelectrochemical systems are already having major impact through numerous scientific innovations that will undoubtedly contribute to the achievement of a circular economy and will continue to make significant contributions to key challenges globally in environmental management, sustainable energy production, resource recovery, healthcare and industrial process optimisation. However, there are still several challenges that must be addressed to improve its use and accessibility. Important among these are the issues of scalability, long-term stability, and efficiency of BES components. Further research and development are required in these areas. There are new and exciting opportunities for innovation that can be realised through the integration of BES with the on-going and new developments in material science, nanotechnology, engineering and synthetic biology. To realise the full potential of BES, there is a need to strengthen existing and expand new inter- or multi-disciplinary collaborations to enable broader diversification and application of the systems. The next generation of BES technologies will be driven by the convergence of knowledge and expertise from microbiology, electrochemistry, materials science, nanotechnology and engineering. This will consequently enable considerable revolutionization in waste management, energy production, resource recovery, environmental remediation and healthcare management and treatment [4–9].

As this field continues to develop and make significant contributions toward achieving the goals of a circular economy, the new journal, “*Bioelectrochemical Systems and Applications*”, aims to play a key and essential role as a hub for the advancement of BES through the dissemination of knowledge and cutting-edge research among scientists, engineers and relevant industry professionals. We welcome all manuscripts on innovative research, theoretical insights, reviews and practical experimental findings on BES that are solving key issues of global concern and that can make significant contribution to the circular economy. We guarantee that all manuscripts submitted will undergo a rigorous peer review process to ensure that only high-quality and high impact research are published in the journal.

Conflicts of Interest: The author declares no conflict of interest.

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