ARTICLE IN PRESS

Biotechnology Advances xxx (xxxx) xxx

Contents lists available at ScienceDirect

Biotechnology Advances

journal homepage: www.elsevier.com/locate/biotechadv

Research review paper

Microbial electrosynthesis: Towards sustainable biorefineries for production of green chemicals from CO_2 emissions

Paolo Dessì [a,*], Laura Rovira-Alsina [b], Carlos Sánchez [c], G. Kumaravel Dinesh [a], Wenming Tong [a], Pritha Chatterjee [d], Michele Tedesco [e], Pau Farràs [a], Hubertus M.V. Hamelers [e], Sebastià Puig [b]

[a] School of Chemistry and Energy Research Centre, Ryan Institute, National University of Ireland Galway, University Road, H91 TK33 Galway, Ireland
[b] LEQUiA, Institute of the Environment, University of Girona. Campus Montilivi, Carrer Maria Aurèlia Capmany 69, E-17003, Girona, Spain
[c] Microbiology Department, School of Natural Sciences and Ryan Institute, National University of Ireland Galway, University Road, H91 TK33, Galway, Ireland
[d] Department of Civil Engineering, Indian Institute of Technology, Hyderabad, India
[e] Wetsus, European Centre of Excellence for Sustainable Water Technology, Oostergoweg 9, 8911, MA, Leeuwarden, The Netherlands

ARTICLE INFO

Keywords:
Bioelectrochemistry
Circular economy
CO_2 reduction
Electrochemical cell
Gas fermentation
Microbial electrochemical technologies
Product purification
Scale-up

ABSTRACT

Decarbonisation of the economy has become a priority at the global level, and the resulting legislative pressure is pushing the chemical and energy industries away from fossil fuels. Microbial electrosynthesis (MES) has emerged as a promising technology to promote this transition, which will further benefit from the decreasing cost of renewable energy. However, several technological challenges need to be addressed before the MES technology can reach its maturity. The aim of this review is to critically discuss the bottlenecks hampering the industrial adoption of MES, considering the whole production process (from the CO_2 source to the marketable products), and indicate future directions. A flexible stack design, with flat or tubular MES modules and direct CO_2 supply, is required for site-specific decentralised applications. The experience gained for scaling-up electrochemical cells (*e.g.* electrolysers) can serve as a guideline for realising pilot MES stacks to be technologically and economically evaluated in industrially relevant conditions. Maximising CO_2 abatement rate by targeting high-rate production of acetate can promote adoption of MES technology in the short term. However, the development of a replicable and robust strategy for production and *in-line* extraction of higher-value products (*e.g.* caproic acid and hexanol) at the cathode, and meaningful exploitation of the currently overlooked anodic reactions, can further boost MES cost-effectiveness. Furthermore, the use of energy storage and smart electronics can alleviate the fluctuations of renewable energy supply. Despite the unresolved challenges, the flexible MES technology can be applied to decarbonise flue gas from different sources, to upgrade industrial and wastewater treatment plants, and to produce a wide array of green and sustainable chemicals. The combination of these benefits can support the industrial adoption of MES over competing technologies.

1. Introduction

Climate change has become one of the most challenging issues faced by humanity. After signing the Paris agreement in 2015, most countries worldwide committed to decreasing their greenhouse gas (GHG) emissions to contain global warming to 2°C (above pre-industrial levels), aiming to 1.5°C by 2050 (United Nations, 2015). Accordingly, the European Union (EU) set a target of 20% GHG reduction by 2020, 40% by 2030 and of achieving a net-zero carbon economy by 2050. The legislative pressure of EU on carbon emissions allowed to achieve the 2020 target already in 2017, when a total of 4483 Mt CO_2eq were produced, 22% lower than the emissions in 1990 (European Environment Agency, 2019). However, EU economy remains largely dependent on fossil fuels, which currently account for 65% of the energy supply and

---

Abbreviations: BMED, Bipolar membrane electrodialysis; CCS, Carbon capture and storage; CCU, Carbon capture and utilisation; CE, Coulombic efficiency; CEM, Cation exchange membrane; CHP, Combined heat and power; COD, Chemical oxygen demand; ED, Electrodialysis; EDI, Electrodeionisation; FO, Forward osmosis; GDE, Gas diffusion electrode; GHG, Greenhouse gas; IL, Ionic liquid; LED, Light emitting diode; LLE, Liquid-liquid extraction; MES, Microbial electrosynthesis; MFC, Microbial fuel cell; NF, Nanofiltration; PEM, Proton exchange membrane; PMS, Power management system; SCE, Solar conversion efficiency; SHE, Standard hydrogen electrode; TLA, Trilaurylamine; TOA, Trioctylamine; TOPO, Tri-n-octylphosphine oxide; VFA, Volatile fatty acid.

[*] Corresponding author.

E-mail address: paolo.dessi@nuigalway.ie (P. Dessì).

https://doi.org/10.1016/j.biotechadv.2020.107675
Received 14 July 2020; Received in revised form 11 November 2020; Accepted 25 November 2020
Available online 1 December 2020

Please cite this article as: Paolo Dessì, *Biotechnology Advances*, https://doi.org/10.1016/j.biotechadv.2020.107675

80% of the total GHG emissions (European Environment Agency, 2019). Significant efforts and innovative measures need to be developed to achieve the ambitious target of net-zero carbon emissions by 2050. Such efforts were translated into the European Green Deal, in which the EU will invest over one trillion euros to promote a low-carbon circular economy (European Commission, 2020).

CO_2 accounts for 65% of GHG emissions worldwide and the resulting environmental issues have contributed to change the paradigm towards its recycling (Aresta et al., 2013). CO_2 is indeed a resource that can be converted to carbon-neutral chemical commodities and fuels using carbon capture and utilization (CCU) technologies, with a future potential at the gigatonne scale (Bains, 2017). CCU technologies will mitigate GHG emissions both directly, by capturing CO_2 that would be otherwise released to the atmosphere, and indirectly, by displacing fossil fuel-based chemicals and fuels currently used by industries with green alternatives. It was estimated that every ton of heavy fuel displaced would avoid emissions of 300-500 g CO_2eq to the atmosphere (Masnadi et al., 2018), which is also valid for fossil fuel-derived chemicals.

Microbial electrosynthesis (MES) is a promising CCU technology for bio-electro CO_2 recycling into valuable chemical products, including organic acids (Batlle-Vilanova et al., 2017; Jourdin et al., 2015), alcohols (Arends et al., 2017; Gavilanes et al., 2019; Vassilev et al., 2019), and bioplastics (Pepè Sciarria et al., 2018). MES cells are essentially composed of two electrodes (cathode and anode), typically separated by a cation-exchange membrane (CEM), hosting a reductive (CO_2 bioreduction) and an oxidative (*e.g.* oxidation of water or organic compounds) reaction, respectively (Fig. 1). CO_2 conversion into organic acids is catalysed by microorganisms that uptake electrons directly from the electrode or indirectly through intermediates such as (bio)electrochemically produced hydrogen (Nevin et al., 2010; Rabaey and Rozendal, 2010).

The use of microbial catalysts provides several advantages in comparison to conventional thermo-electrocatalytic CO_2 reduction. Microorganisms are cheap and self-regenerating catalysts that can achieve >80% electricity-to-product conversions under mild temperature (*i.e.* ambient or mesophilic conditions) (Bajracharya et al., 2017a). However, further efforts are required to optimise the conversion rate/yield and purity of products in MES reactors, and research on scaling-up CO_2 reduction processes is still scarce (Sánchez et al., 2019). The experience acquired in scaling-up related technologies such as commercially available electrolysers, as well as pilot-scale microbial fuel cells (Dong et al., 2015; Feng et al., 2014; Liang et al., 2018; Rossi et al., 2019; Vilajeliu-Pons et al., 2017), and microbial electrolysis cells (Gil-Carrera et al., 2013), can offer guidelines for deploying scalable MES configurations.

MES is currently a hot topic in biotechnology, and recent reviews gave an excellent summary of key aspects of the technology, from fundamental microbiology and electron transfer aspects (Karthikeyan et al., 2019; Logan et al., 2019) to the current state-of-art and future perspectives (Bian et al., 2020; Fruehauf et al., 2020; Jiang et al., 2019; Jiang and Jianxiong Zeng, 2018; Prévoteau et al., 2020), as well as techno-economic feasibility (Jourdin et al., 2020). Here we reviewed the main aspects hindering MES commercialisation, including the integration of MES reactors in industrial plants, reactor design, product synthesis and purification, and use of renewable electricity. Key issues were individuated, and future directions were suggested, based on previous experience on similar technologies, for putting forward resilient and sustainable CO_2 recycling MES biorefineries.

2. Integration of MES into industrial plants

2.1. CO_2 sources for MES

Energy supplies, together with industry and transportation, generate most greenhouse gas emissions in EU (1.27, 0.88 and 0.95 Gton CO_2eq/year, respectively). The energy sector accounts for 92.4% of the total CO_2 emissions, where energy generation (34.8%), transport (29.6%), and the manufacturing industry (15.4%) are the main contributors. The remaining non-energy related CO_2 emissions are mainly produced by the mineral, metal, and chemical industry (Fig. 2). MES is a bioelectrochemical recycling platform for CO_2 conversion to valuable products that can be directly applied for decarbonisation of flue gases from the energy supply and carbon-intensive industry sectors such as steel mills (20-30% CO_2), ceramic (15-20% CO_2), glass (10-15% CO_2), refineries (10-20% CO_2), cement industries (25-30% CO_2), and power plants (10-15% CO_2). Furthermore, MES can potentially recycle CO_2 produced from biological processes such as anaerobic digestion, fermentation and conventional wastewater treatment, which has been

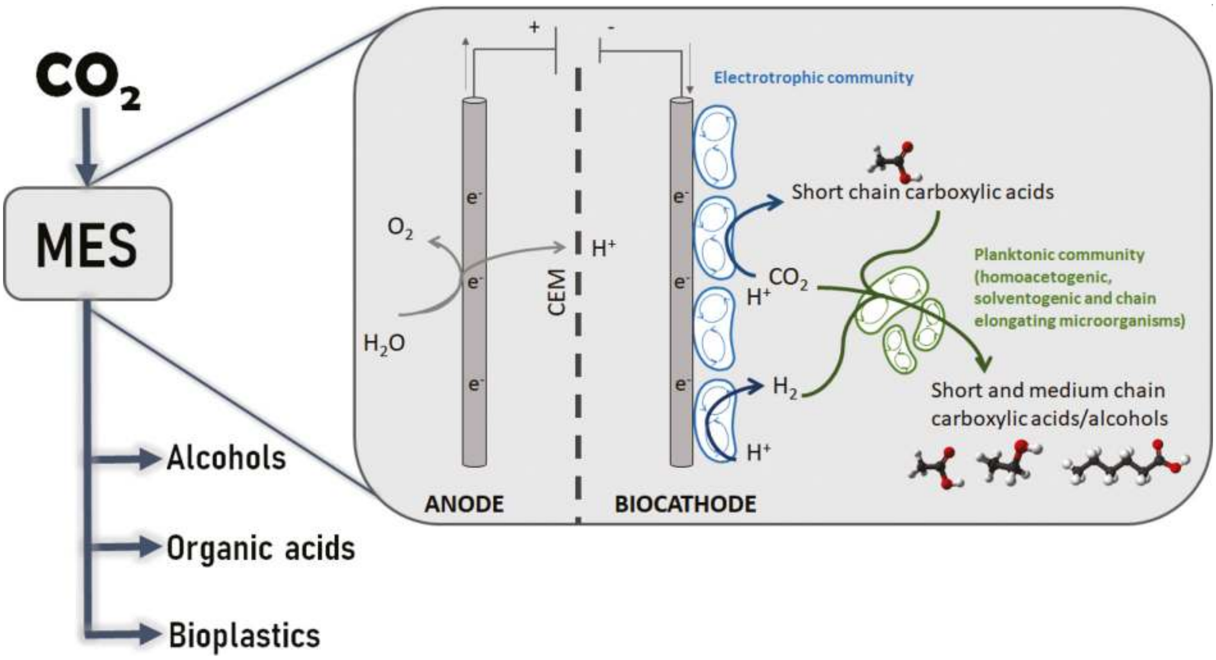

Fig. 1. Schematic representation of a typical MES configuration for biocommodities production from CO_2.

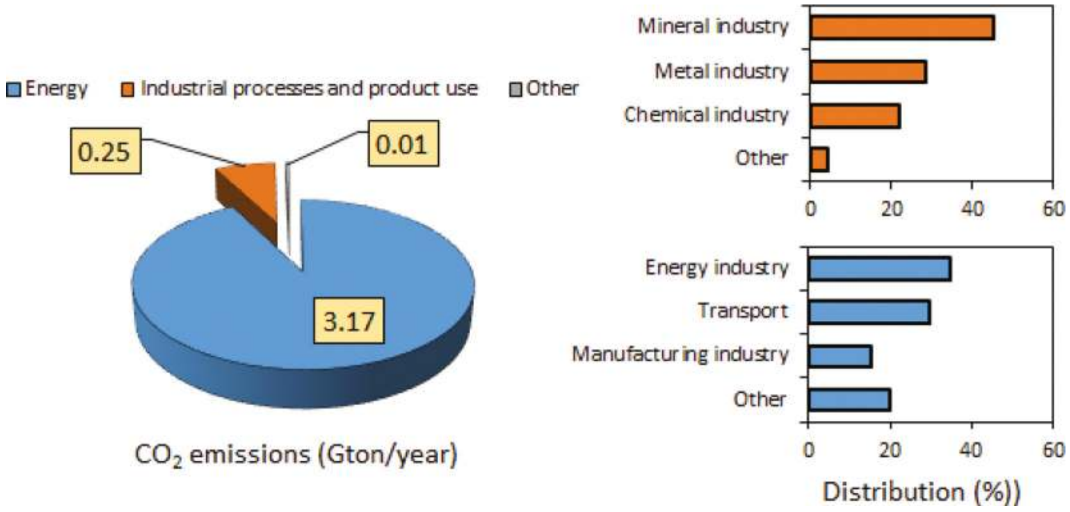

Fig. 2. Sectorial distribution of the CO_2 production in EU and relative contributions of CO_2 emissions from the energy (blue) and industrial processing (orange) sectors. The graphs were generated from the European Environmental Agency (EEA) database 2018.

estimated to produce around 4.4 × 10^{-3} Gton CO_2/year worldwide (Rosso and Stenstrom, 2008).

2.2. CO_2 capture and utilisation in MES devices

Applying MES to industry requires infrastructures for gas transportation to the MES reactor, which inevitably lead to a higher footprint and costs. By performing a sensitivity analysis on the major costs associated to the adoption of carbon capture and storage (CCS) technologies in the iron and steel, cement and petroleum refining industries, Leeson et al. (2017) estimated that CO_2 capture and transportation can cost as high as 180 €/ton CO_2. Hence, integrated MES plants on industrial sites (*i.e.* close to the CO_2 emission sources) present a more economically viable solution than centralised plants. This highlights the need for designing flexible MES reactors, adaptable to the gas volumes and composition of the specific industry requiring gas treatment. Furthermore, when spent gasses are released during combustion, *e.g.* in boilers on combined heat-power (CHP) plants, reducing the temperature to 20-30°C is required prior to feeding it to the MES cell. Such excess of heat can be recovered, using heat exchangers, and used for warming up the MES reactors, or recycled to other applications to further reduce operational costs. Another option is to operate MES reactors under thermophilic conditions, thereby increasing the production kinetics and reducing the risk of microbial contamination, although the lower gas solubility at high temperature may limit the carbon and energy availability (Rovira-Alsina et al., 2020).

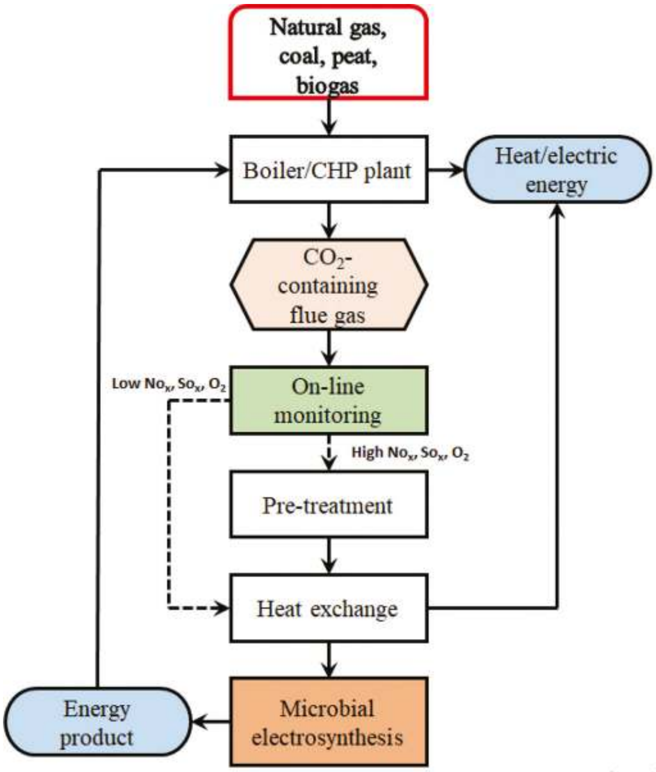

Fig. 3. Example of integration of MES for treatment of CO_2-containing flue gas from the combustion of carbonaceous fuels. MES energy products (*e.g.* methane or alcohols) can be blended to the fossil fuels, further decreasing the carbon footprint of power plants.

Depending on waste gas components, a pre-treatment may be required to remove impurities and toxic compounds for the MES microbial community (Fig. 3). This is the case, for example, of power plants powered by coal, peat or crude oil combustion, producing a gas containing CO, O_2, SO_X, NO_X, HCl and particulate ash besides CO_2 (Aouini et al., 2014; Pihu et al., 2017). In contrast, CO_2 constitutes 96-99% of flue gas produced in natural gas processing and alcohol fermentation. Complete natural gas combustion with air generates a clean flue gas stream of nitrogen (72% wt.), CO_2 (15-17%) and moisture (10-11%) (Sonibare and Akeredolu, 2004), which can be directly fed to MES reactors due to the absence of toxic compounds. Lab-scale MES reactors were indeed successfully operated on N_2:CO_2 80:20% mixture gas feed (Deutzmann and Spormann, 2017; Nevin et al., 2010; Russell, 2013; Tahir et al., 2020; Zhang et al., 2013). In case of incomplete combustion, CO, NO_X and residual O_2, detrimental for the microbial community, are also released, and on-line monitoring of the flue gas is thus required to prevent system breakdown. Nevertheless, regulations on CO, SO_X and NO_X emissions are, or will be, in place at the global level and thus, industries already have, or will require, a technology to remove these contaminants from flue gas. Oxygen concentration should also be minimised, since it can reduce MES efficiency by inhibiting the strictly anaerobic microorganisms, particularly in the absence of oxygen scavenging species (*e.g.* when oxygen-sensitive pure cultures are used as a microbial catalyst) (Giddings et al., 2015). Furthermore, O_2 exposure causes a decrease of the Coulombic efficiency (CE) by promoting the biological oxidation of MES organic products (Marshall et al., 2013), as well as diverging electrons towards O_2 electrochemical reduction into water.

The carbon capture cost is highly variable concerning the flue gas composition and increases with the level of CO_2 purity required (Bains, 2017; d'Amore et al., 2019; Leeson et al., 2017). In MES, the pre-treatment target is to reduce contaminants (*e.g.* NO_X, SO_X, and O_2) below the tolerance limit of the microorganisms, rather than generating a pure CO_2 stream, resulting in lower costs. Several SO_X and NO_X removal technologies are commercially available, being desulfurisation with lime or limestone, and catalytic NO_X reduction, respectively, the most commonly applied worldwide (Sun et al., 2016). Furthermore, since CO_2 is a by-product of both processes when urea is used as reductant, it will contribute to the overall CO_2 feedstock for the MES cells. If the O_2 concentration in flue gas exceeds the tolerance of the MES community, a CO_2/O_2 separation step, such as adsorption or membrane separation (Wilberforce et al., 2019), is also required.

2.3. *Reactor design for scale-up*

Due to their simplicity, H-type MES cells have been commonly used for lab-scale experiments (Deutzmann and Spormann, 2017; Gavilanes et al., 2019; Mohanakrishna et al., 2020). Such design, however, is not an optimal solution for scale-up, due to (i) the large area requirements, (ii) the lack of modularity and versatility, and (iii) the high ohmic losses associated to low electrode surface/volume capability, low membrane surface, inefficient hydrodynamics, and a large distance between anode and cathode.

Since in bioelectrochemical systems the overpotential (*i.e.* the extra-voltage required for a reaction to occur in comparison to the theoretical) unavoidably increases with the reactor size (Rossi et al., 2019), a small, compact, and stackable reactor design is preferable for scaling-up rather than a single, large volume reactor (Greenman and Ieropoulos, 2017). Furthermore, stacks with several MES cells facilitate maintenance, since individual cells can be stopped without affecting the operation of the other cells. Multi-chamber reactors with flat (Bajracharya et al., 2016; Srikanth et al., 2018b) or tubular (Batlle-Vilanova et al., 2017; Blasco-Gómez et al., 2019; Pepè Sciarria et al., 2018) structures are examples of easily scalable and stackable configurations to increase the electrode surface/volume ratio and reduce area requirements. Projected surface/volume ratios above 1 cm^2/mL are achievable with flat MES configurations (Srikanth et al., 2018b), and can be further optimised, although the limitations of the microbial catalysts will hamper to reach the extremely low electrolyte volumes of up-to-date electrochemical electrolysers (Haas et al., 2018; Yin et al., 2019).

MES stacks can be operated with either series or parallel hydraulic and electric connections. Modules hydraulically connected in parallel receive the same feed rate, favouring replicability, whereas modules connected in series will receive a decreasing CO_2 load, thereby resulting in higher overall CO_2 removal efficiency (Fig. 4). However, the configuration in series is more exposed to the toxic effect of contaminants, if present in the flue gas to be treated, whereas the contaminant load is distributed when MES cells are connected in parallel. Therefore, a hybrid configuration, with parallel lines connected in series (Fig. 4), could be an advantageous solution. The number of parallel lines required can be dimensioned based on the waste flue gas production and reaction rates, whereas the length of the cell series is proportional to the required CO_2 removal efficiency. When comparing the electric configurations, superior performance of parallel than series connection was reported for bioelectrochemical systems stacks (Jafary et al., 2013; Liu et al., 2016). Connection in series could cause operation problems such as polarity reversal and substrate cross-conduction effect, and the resulting parasitic current flows (Gurung and Oh, 2012; Zhuang et al., 2012). Thus, connections in parallel appear preferable for MES, since a reliable cathode potential control (*e.g.* between -0.6 and -1.0 V *vs.* standard hydrogen electrode, SHE) is required, and because connections in parallel result in higher current densities than in series (Gurung and Oh, 2012). However, since MES cells are not identical, low resistance paths may occur in the MES stacks, requiring further potential control, as explained in Section 5.3.

Reporting on MES scaling-up is highly limited, and to date no pilot- or full-scale MES system is reported for CO_2 conversion. However, design of commercially available electrochemical cells, such as electrolysers, can be potentially applied to scale-up the MES systems with minor modifications, and available pilot-scale studies on other bioelectrochemical systems, such as microbial fuel cells (MFCs), can provide useful guidelines. Configurations of scaled-up, stacked bioelectrochemical systems have been applied for the treatment of swine manure (Vilajeliu-Pons et al., 2017), brewery wastewater (Dong et al., 2015), and municipal wastewater (Feng et al., 2014; Liang et al., 2018; Rossi et al., 2019), as well as ammonia recovery (Zamora et al., 2017). So far, the largest scaled-up bioelectrochemical system is a 1000 L MFC (Liang et al., 2018), a device in which electric energy is produced by

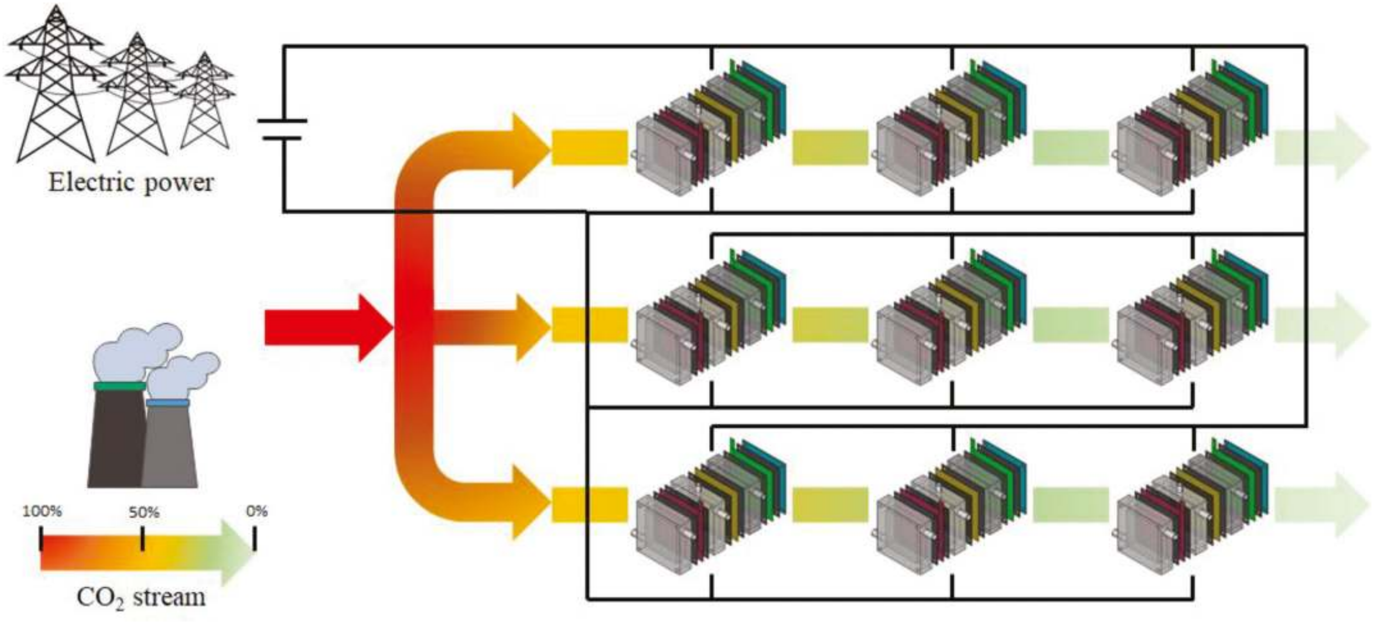

Fig. 4. Example of MES reactor stacks with hydraulic connections both in parallel and in series, and electric connections in parallel.

biological oxidation of organic or inorganic contaminants and subsequent electron transfer to an electric circuit. It consisted of 50 squared modules (20 L each), electronically connected in parallel. A similar configuration, with the integration of CO_2 feeding lines, can be adapted to MES cells.

Flue gas can be delivered to MES reactors essentially in three ways: (i) CO_2 solubilisation and feeding as bicarbonate, (ii) direct gas feeding using gas spargers, or (iii) gas diffusion electrodes (Fig. 5). Dissolving CO_2 into a liquid bicarbonate-containing stream could simplify MES operation and improve the carbon conversion efficiency (Srikanth et al., 2018a). However, it requires an additional step for CO_2 solubilisation, leading to higher costs and area requirement. Direct gas utilisation requires more sophisticated design and control (*e.g.* gas composition and pressure monitoring) but is a more viable option in terms of costs and space utilisation. When gas spargers are used in MES, promoting contact between CO_2 and microorganisms is key to reach high production rates. This can be achieved by (i) maximising the active electrode surface by filling the cell with conductive granules (Vassilev et al., 2018), (ii) using electrodes with a high specific active surface such as multi-walled carbon nanotubes (Jourdin et al., 2016; Jourdin et al., 2015), (iii) forcing the CO_2 flow towards the electrode, *e.g.* using hollow fibre cathode electrodes (Katuri et al., 2018), or (iv) recirculating gas from the reactor headspace (Mateos et al., 2019).

Gas diffusion electrodes (GDEs) represent an effective alternative for decoupling the MES process from CO_2 solubilisation. GDEs, first applied to a MES reactor by Bajracharya et al. (2016), consist of a combination of hydrophobic polymeric gas diffusion and catalyst layers, enabling a three-phase (gas-liquid-solid) interphase that allows keeping high CO_2 concentrations in proximity of the (bio)catalyst. GDEs have been applied in lab-scale MES devices to produce both carboxylic acids and alcohols with production rates of 238 mg/(L·d) acetic acid (Bajracharya et al., 2016), 360 mg/(L·d) formate and 141 mg/(L·d) ethanol (Srikanth et al., 2018b). Multi-panel GDEs have also been applied as air diffusion cathodes in pilot-scale MFCs treating municipal wastewater with each panel having a surface of 324 cm^2 (Hiegemann et al., 2019; Rossi et al., 2019). Both studies reported a reduction of MFC performance over time due to fouling, which, nevertheless, is a minor issue in MES reactors owing to the low growth rate of autotrophic microorganisms and the relatively pure catholyte. Therefore, with such flexibility and efficiency, GDEs are promising electrodes for scaling-up MES.

Minimising the electrolyte volumes along with circulating the catholyte and anolyte towards and away from the respective electrodes is a scalable design solution discerning cell architecture, which is adopted in commercial-scale water electrolysers and fuel cells (Weekes et al., 2018). Such setup requires a separator to split apart the reduction and oxidation reactions occurring at the cathode and anode, respectively, promoting proton transfer while limiting O_2 flow from the anodic to the cathodic chamber. Proton exchange membranes (PEMs) such as Nafion, widely used in MES lab-scale devices (Kracke et al., 2019; Mohanakrishna et al., 2020; Srikanth et al., 2018b), are expensive. PEMs can cost as high as 2500 €/m^2 and represent up to 30-40% of the capital costs in both electrolysers and MFCs (Chakraborty et al., 2020; Mayyas et al., 2019). Cheaper options such as textile separators (Dong et al., 2015), as well as membrane-electrode assemblies (Salar-García et al., 2016) and membrane-less configurations (Feng et al., 2014; Hiegemann et al., 2019; Thung et al., 2019; Walter et al., 2020) have been generally preferred for scaling-up MFCs for wastewater treatment, and are potential solutions for MES as well. Low-cost ceramic separators were shown to achieve comparable, or even higher CE than Nafion membranes in MFCs (Khalili et al., 2017). Porous ceramic diaphragm separators are already available at commercial scale for alkaline electrolysis (Ursúa et al., 2012), and can replace expensive ion exchange membranes

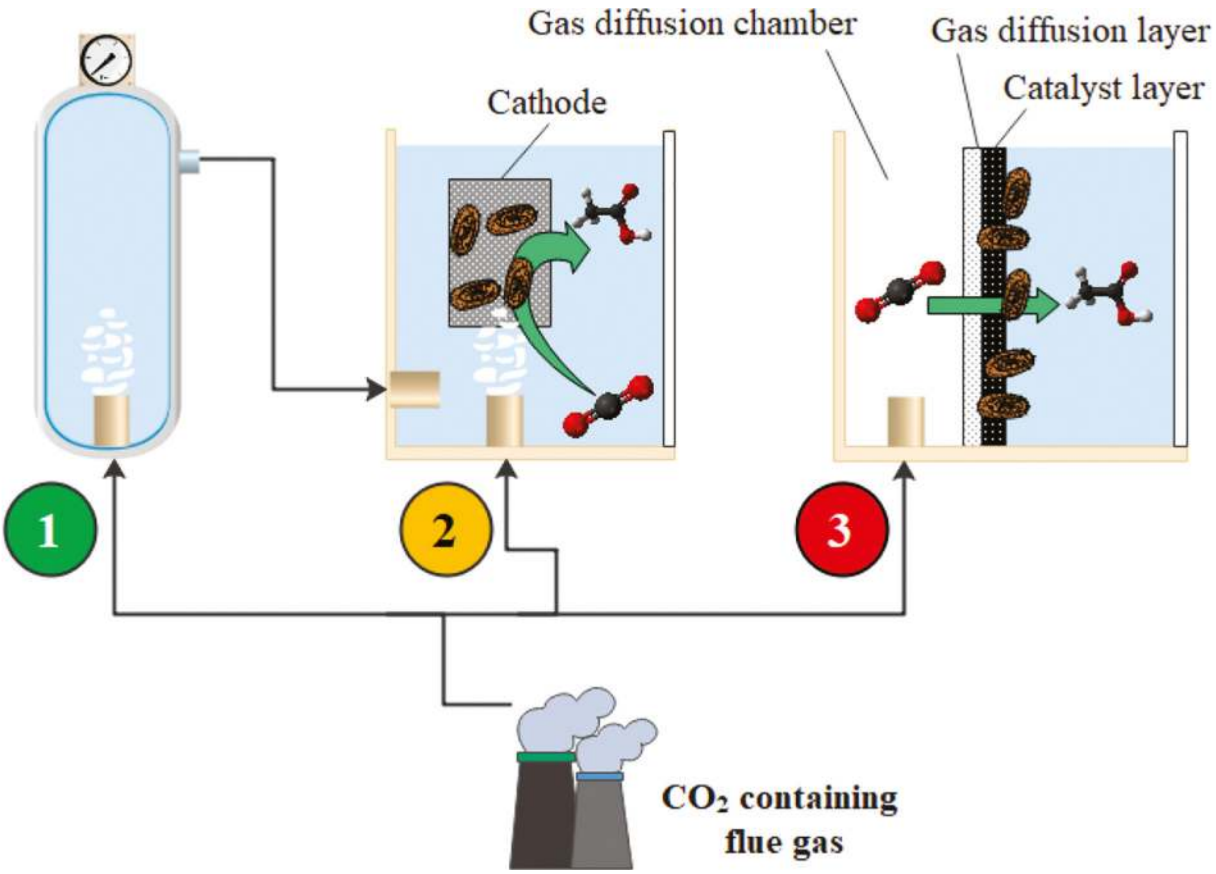

Fig. 5. CO_2 feeding strategies to MES reactors. CO_2 can be solubilised in a pressurised reactor and then delivered to the MES reactor (1), or directly delivered to the MES reactor through a sparger (2) or gas diffusion electrode (3).

in MES.

Membrane-less MES systems can eliminate the costs and ohmic drops associated to separators, but oxygen diffusion towards the cathode needs to be prevented (Butler and Lovley, 2016). A membrane-less MES reactor, in which the CO_2-containing gas sparged from the bottom of the reactor was used to mitigate oxygen diffusion from the anode towards the cathode, was proposed by Giddings et al. (2015). However, the acetic acid production rate of 1.7-2.2 $g/(m^2 \cdot d)$ achieved using *Sporomusa ovata* was substantially lower than that of 2.7-3.4 $g/(m^2 \cdot d)$ obtained with the same strain using Nafion membranes (Russell, 2013; Zhang et al., 2013). A membraneless cell was also proposed for biomethane production from CO_2, achieving a production rate of 4.7 $L/(m^2 \cdot d)$ (Giang et al., 2018). Microfluidic cells, with anode and cathode divided by a thin layer of electrolyte in which CO_2 diffuses, are an emerging technology for CO_2 electrolysis (Weekes et al., 2018), potentially applicable to designing membrane-less MES reactors with minimal distance between electrodes. However, scaling-up of such technology, hardly operable under pressure, is more problematic than traditional setups with membranes (Sánchez et al., 2019).

3. Carbon recycling in MES

3.1. Biocatalysts

Numerous microorganisms from all three domains of life have revealed ability to interact with solid electrodes for their metabolism (Logan et al., 2019). They are classified as exoelectrogens or electrotrophs, respectively, based on their ability of transferring electrons to, or accepting electrons from, an electrode. So far, four types of proteins have been identified to be responsible for electron transfer between electrode and cell surface: (i) porin-cytochrome complexes, (ii) cell-surface cytochromes, (iii) conductive nanowires and (iv) other redox proteins, including copper and iron-sulfur proteins (Costa et al., 2018). Electrotrophs are the core of MES cells, acting as the catalyst for CO_2 conversion to a wide array of valuable products (Lee et al., 2019). They can reduce CO_2 by uptaking electrons either directly from the cathode electrode, or through mediators such as H_2, formate, ammonia, Fe^{2+}, or even more complex molecules such as self-produced flavins (Tremblay et al., 2017). Mixed microbial consortia and pure cultures of specific microorganisms, either natural or genetically modified, can act as biocatalyst in MES cells. Each inoculation strategy has its own advantages and disadvantages, as summarized in Table 1.

Table 1
Advantages and disadvantages of the different biocatalysts for MES.

Type of biocatalyst	Advantages	Disadvantages
Mixed microbial culture	+ Easy to operate + Widely available + Resistant to system fluctuations + Resistant to O_2 intrusion + Easy start-up upon failure	- Prone to membrane biofouling - Low selectivity for products other than acetate - Possible competition between acetogens and methanogens and/or establishment of other competitors
Pure microbial culture	+ High selectivity + Easy optimisation for highest production rates-yields + Prevents growth of competitors	- Laborious start-up procedure - Requires a specific growth medium - Requires sterilisation - Vulnerable to system fluctuations - Vulnerable to O_2 intrusion
Genetically modified microorganisms	+ Same advantages of pure microbial cultures + Wider product spectrum and selective production of high-value molecules + Can be made resistant to system fluctuations and O_2	- Expensive and laborious start-up procedure - Requires a specific growth medium - Requires sterilisation - Questionable societal acceptance - Requires approval by the government

Mixed cultures from natural and anthropogenic environments have been widely used as biocatalyst in bench-scale MES cells for production of methane (Geppert et al., 2019; Jiang et al., 2013), acetate (Jourdin et al., 2015; Mateos et al., 2019), as well as mixtures of medium-chain carboxylic acids (Batlle-Vilanova et al., 2017; Vassilev et al., 2019, 2018) and alcohols (Arends et al., 2017; Blasco-Gómez et al., 2019; Gavilanes et al., 2019; Srikanth et al., 2018b) from CO_2. Mixed cultures represent the easiest and cheapest inoculation strategy for MES, but the low product selectivity (except for acetate) and the possible competition between acetogenic and methanogenic microbial communities are still unresolved challenges.

In comparison to mixed cultures, pure cultures offer higher product selectivity and eliminate competition issues. However, handling of pure cultures is laborious, requiring sterilization and a stable ecosystem. Nonetheless, avoiding contamination in CO_2-fed cells appears easier than in reactors treating solid or liquid waste, making the use of pure cultures suitable for industrial MES applications. Among pure cultures, acetogenic bacteria including *Sporomusa ovata*, *S. sphaeroides*, *Clostridium ljungdahlii* and *Moorella thermoacetica* have been confirmed to reduce CO_2 to acetate by accepting electrons from a MES cathode (Nevin et al., 2011; Nevin et al., 2010), whereas other microorganisms such as *Acetobacterium* sp. exploit locally produced H_2 as the electron source (Marshall et al., 2017). Indirect (H_2-mediated) electromethanogenesis was reported by using a pure culture of *Methanococcus maripaludis* that converted CO_2 and on-site electrochemically produced H_2 to methane (Kracke et al., 2020). H_2-mediated electron transfer has been postulated to be less energy efficient than direct electron transfer (Karthikeyan et al., 2019), in which, nevertheless, the production yields can suffer of low electron exchange rates.

Genetic engineering approaches have been proposed to overcome the limitation of microorganisms in terms of electron transfer rates and cathode interaction, as well as to manipulate the metabolic pathways to target specific biocommodities (Shin et al., 2017). Metabolic engineering can provide a reliable method to go beyond the low-value chemicals naturally produced at the cathode (*e.g.* acetate), and achieve high-rate production of more valuable chemicals that are typically obtained in traces (*e.g.* multi-carbon chain biochemicals and biofuels (Kracke et al., 2018). However, an insufficient knowledge of the fundamental mechanisms is limiting the adoption of genetic engineering in MES, and research efforts are required to expand the toolset available for manipulating electricity-driven metabolic pathways. Furthermore, the high costs, as well as the legislative requirements, summarized in the review from Voeikova et al. (2020), make this approach complicated and economically dependent on the production capacity and value of the output products.

3.2. Production rates and product selectivity

Acetic acid is, to date, the major product obtained with MES. The highest specific production rate of 790 $g/(m^2 \cdot d)$ was achieved using three-dimensional (3D) macroporous cathodes, far beyond the production rate obtained with unmodified carbon-based electrodes (Jourdin et al., 2018; Jourdin et al., 2016). Acetic acid can be produced from CO_2 in MES with high selectivity (>90%), and CE exceeding 85% (Nevin et al., 2010). Despite the developments in electrode design, the acetic acid production rate is limited by the low current densities, typically below 20 mA/cm^2, which is one order of magnitude lower than those achieved in electrolysers (Prévoteau et al., 2020). In MES, besides the inherent limitations of the biological catalysts, the current density is limited by the kinetically unfavourable oxygen evolution reaction at the anode. This is particularly relevant when carbon electrodes are used, resulting in potential differences as high as 3 V, or even more, between cathode and anode (Bian et al., 2020). Furthermore, the anode has been individuated as the highest contributor to capital expenditure in MES cells (Jourdin et al., 2020). Using photoanodes, or exploiting less energy-demanding (bio)reactions at the anode, such as the oxidation of organic pollutants, are potential solutions currently under investigation (described in Section 5.2).

Methane can be produced at biocathodes in alternative to acetic acid. So far, the highest methane production rate of 12.5 L/(L·d), with 65% current-to-methane efficiency, was achieved using a mixed culture from a biogas plant in a galvanostatic flow-cell designed to maximise surface area (2 cm^2/cm^3) and optimise flow distribution (Geppert et al., 2019). In this study, the methane production rate was shown to increase linearly with the applied current (in the range 0.5-3.5 mA/cm^2), although hydrogen was detected at currents above 2.5 mA/cm^2, suggesting metabolic limitations of the biocatalyst. Methane has often been reported as co-product in acetogenic MES (Marshall et al., 2013; Patil et al., 2015). When mixed cultures are used as inoculum, and when MES cells are operated at neutral pH, methanogenic organisms can indeed compete with acetogens for H_2, or even convert carboxylic acid into methane. Methanogenic growth can be prevented by pre-treating the inoculum, *e.g.* by heat (Bajracharya et al., 2017c) or chemical treatment (Marshall et al., 2013), although these procedures do not ensure their permanent elimination.

The product spectrum of MES has expanded away from acetic acid towards more valuable compounds in the past few years, being butyrate and caproate two of the main products of interest (Table 2). Chemical commodities such as formate (Tashiro et al., 2018) and 3-hydroxybutyrate (Chen et al., 2018) have been obtained *via* MES from CO_2 as the sole carbon source using pure cultures and metabolic engineering tools. However, the scalability of this approach remains arguable and requires further investigation. Mixed cultures from different sources, nevertheless, have shown potential for the production of carboxylic acids and alcohols from CO_2 in MES, up-to six-carbon chains (Vassilev et al., 2018). Operation conditions, in particular pH, hydrogen partial pressure and inorganic carbon concentration, can be fine-tuned to steer the production of the target compound (Blasco-Gómez et al., 2019). In MES, pH can be controlled by CO_2 sparging, without the need for added chemicals (Bajracharya et al., 2017c; Ganigué et al., 2015), which represents a key advantage for full-scale applications. Low pH ($<$ 5.5) has been observed to promote solventogenesis, whereas pH close to neutrality is more favourable for butyric and caproic acid formation *via* chain elongation (Vassilev et al., 2018). Based on this observation, a dual biocathode arrangement was proposed to set an optimal pH of 6.9 for acetogenesis and chain elongation in one chamber, and a pH of 4.9 to promote solventogenesis in a second chamber (Vassilev et al., 2019). High hydrogen partial pressure was shown to promote acetic acid production rates, as well as solventogenesis, when combined with low pH (Blasco-Gómez et al., 2019), whereas low H_2 partial pressures turned out to favour biological H_2 evolution (Philips, 2020). Otherwise, a high concentration of dissolved CO_2 promotes acetic acid production, but results in lower product diversification (Arends et al., 2017).

Butyrate production from CO_2 in MES was achieved for the first time

Table 2
Biochemicals and biofuels obtained from CO_2 in MES cells operated in potentiostatic (*i.e.* constant voltage operation) or galvanostatic (*i.e.* constant current) mode under different operational conditions.

Product	Highest production rate (g/(L·d))	Main carbon sources	pH	T (°C)	Potentiostatic control (V *vs.* SHE)	Galvanostatic control (mA/cm^2)	Cathode	Reference
	Biochemicals							
Acetate	77	$NaHCO_3$	5.2	35	-1.10	n.a	3D-reticulated vitreous carbon	Jourdin et al. (2016)
	66	$NaHCO_3$	6.7	35	-0.85	n.a	Multi-walled carbon nanotubes	Jourdin et al. (2015)
	18.72	CO_2	7.0	25	n.a.	-83	Reticulated vitreous carbon foam	LaBelle and May (2017)
	9.85	CO_2:N_2 30:70%	5.8	32	-0.85	n.a.	Carbon felt	Jourdin et al. (2018)
	0.26	Brewery flue gas (98% CO_2)	7.0	28	-0.80	n.a.	Graphite plate	Roy et al. (2021)
Butyrate	5.70	CO_2:N_2 30:70%	5.8	32	-0.85	-5 to -12	Carbon felt	Jourdin et al. (2019)
	0.54	Acetate, $(NH_4)_2CO_3$ and CO_2	5.5	30	n.a.	-0.93	Carbon felt	Raes et al. (2017)
	0.16	CO_2	6.3	38	-0.80	n.a.	Carbon cloth	Batlle-Vilanova et al. (2017)
	0.04	CO_2	6.4	35	-0.80	n.a.	Carbon cloth	Ganigué et al. (2015)
Caproate	2.41	Ethanol, CO_2 and $NaHCO_3$	7.0	30	n.a.	-1.0	Carbon felt	Jiang et al. (2020)
	2.00	CO_2:N_2 30:70%	5.8	32	-0.85	-5 to -12[a]	Carbon felt	Jourdin et al. (2019)
Formate	0.36	CO_2	8.0	29	-0.80	n.a.	Gas diffusion electrode	Srikanth et al. (2018b)
	Biofuels							
Butanol	0.06	CO_2	8.0	29	-0.80	n.a.	Gas diffusion electrode	Srikanth et al. (2018b)
Ethanol	0.18	CO_2	8.0	29	-0.80	n.a.	Gas diffusion electrode	Srikanth et al. (2018b)
	0.05	CO_2	5.4	25	-0.80	n.a.	Granular graphite	Blasco-Gómez et al. (2019)
Isopropanol	0.06	CO_2:N_2 10:90%	5.0	30	n.a.	-0.5	Carbon felt	Arends et al. (2017)
Methane	12.5[b]	$NaHCO_3$	7	30	n.a.	-1.0 to -3.5	Graphite felt	Geppert et al. (2019)
	0.53[b]	CO_2	n.a.	30	-0.85	n.a.	Carbon felt	Jiang et al. (2013)

[a] The cell was first operated in potentiostatic mode, and successively in galvanostatic mode; [b] Units in L/(L·d); n.a.: non-available.

by Ganigué et al. (2015), with a production rate of 0.04 g/(L·d). Batlle-Vilanova et al. (2017b) triggered its selective production by operating the reactor at pH close to 5 and hydrogen partial pressure above 1 atm, reaching a maximum rate of 0.16 g/(L·d). Jourdin et al. (2019) reinforced butyrate and caproate production (maximum rates of 5.7 and 2.0 g/(L·d), respectively) by increasing the CO_2 loading rate up to 173.2 L/d. In this study, ethanol was first produced by acetate reduction and then acted as the electron donor for chain elongation. However, in another study (Jourdin et al., 2018), caproate was produced at a rate of 0.95 ± 0.05 g/(L·d), together with acetate (9.8 ± 0.65 g/(L·d)) and butyrate (3.2 ± 0.1 g/(L·d)), but without ethanol production, suggesting that the cathode was acting as the sole electron donor. At low pH, butyric and caproic acid were reduced to the corresponding alcohols (butanol and hexanol), opening possibilities of producing high-value biofuels in MES, although low titers of 0.8 and 0.2 g/L, respectively, were achieved (Vassilev et al., 2018). On the other hand, isopropanol production could be triggered in MES at pH 5 by maintaining low dissolved CO_2 concentrations in the catholyte. The production rate was stable at 5.85 ± 0.17 × 10^{-2} g/(L·d) working under a hydraulic retention time of 5 days (Arends et al., 2017).

3.3. Production strategies

Development of cost-effective MES reactors for CO_2 recycling involves two diverging strategies: (i) maximise production rate of low-value products with high market request (*i.e.* acetic acid or methane), or (ii) steer production towards more valuable products, though at lower production rates (Fig. 6). The first strategy, in which the main target is the abatement of high CO_2 volumes, appears as the most feasible in the short term. Selective acetic acid production *via* MES, with both pure and mixed cultures, has been extensively demonstrated from different inorganic carbon sources, including bicarbonate (Jourdin et al., 2015), pure CO_2 gas (Song et al., 2017), and brewery flue gas (Roy et al., 2021). Versatile mixed cultures can achieve comparable, or even higher, acetic acid production rates than pure cultures, with similar specificity and CEs (Jiang et al., 2019). High product selectivity will make the product downstream processing easier and cheaper. Similarly, methane can be selectively produced in MES cells using widely available methanogenic cultures from biogas plants Geppert et al. (2019).

Despite the technological advances of the field, production rates far beyond the current record are required for MES commercialisation, due to the low value of acetic acid and methane (0.4–0.7 €/kg). When modelling for an industrial production of 1000 tons/year with an assumption of 69% CE, an unsustainable production cost of about 6.6 €/ton acetic acid was estimated, which could be reduced by 33% using renewable energy. Other products such as ethanol (1.0 €/kg) and formate (0.4 €/kg) are more cost-attractive (Christodoulou et al., 2017). Ethanol was also shown to have the most positive effect on GHG emissions, with a negative global warming potential of –753 tons CO_2eq (Christodoulou et al., 2017).

Beyond acetic acid and ethanol, conversion of CO_2 to longer-chain carboxylic acids or alcohols, though with lower production rates, offers an interesting economic perspective. Such products are currently mainly manufactured *via* chemical synthesis from fossil-fuel based precursors. The expected dynamic growth in their market size, in combination with the fees (up to 99 €/ton, with an increasing trend) associated to CO_2 emission (Luckow et al., 2016), can foster the use of CO_2 as an alternative feedstock. Increasing demand for so-called cosmeceutical products is catalysing the global carboxylic acid market, in which compounds such as butyric and caproic acid are extensively used (Future Market Insights, 2020; Global Market Insights, 2020). Due to their high energy density and low hygroscopicity, higher alcohols such as butanol

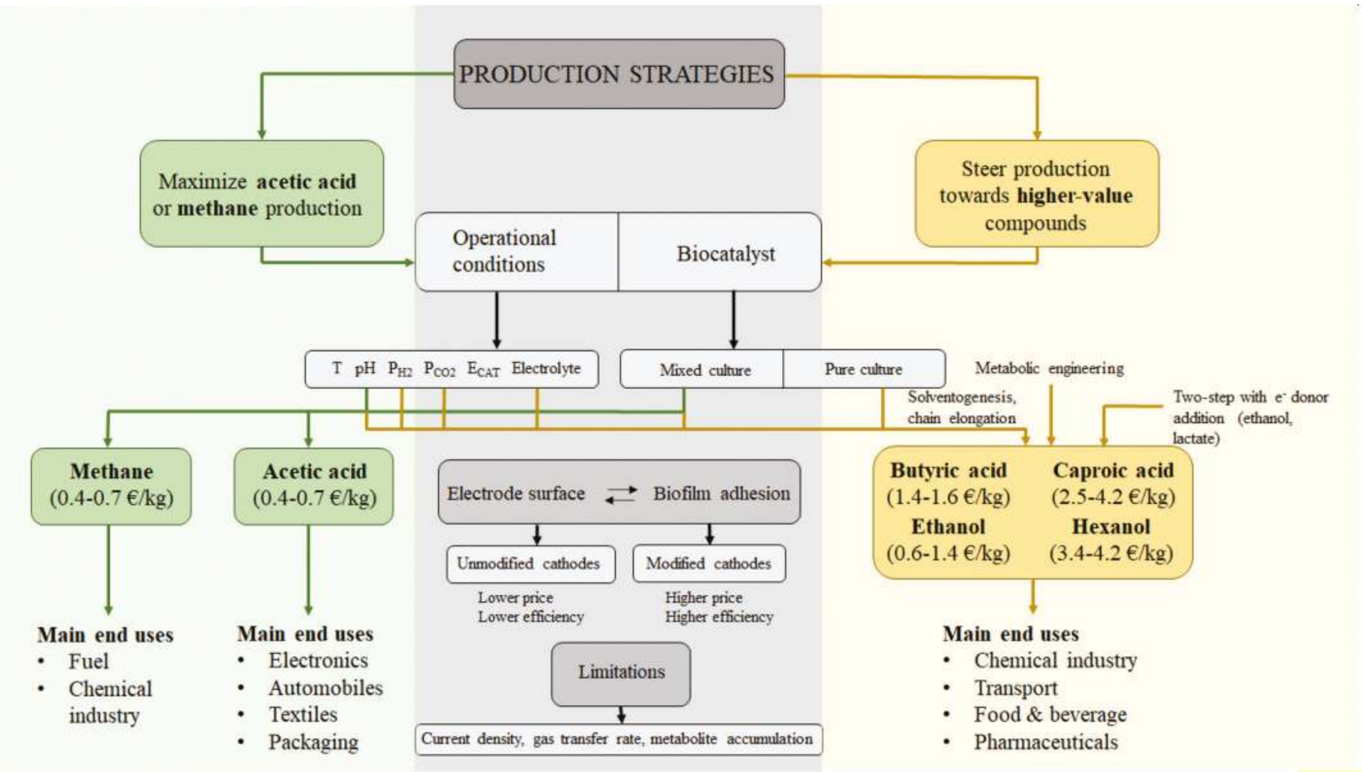

Fig. 6. Production strategies for microbial electrosynthesis of organic compounds from CO_2. Market prices have been obtained from marketsandmarkets.com (acetic acid, ethanol and butyric acid), transparencymarketresearch.com (methane) or alibaba.com (caproic acid and hexanol). Selective acetic acid and methane production can be achieved using mixed cultures. Production of longer-chain carboxylic acid, both using pure and mixed cultures, requires a stricter control of operation parameters such as pH, hydrogen and CO_2 partial pressure (P_{H2} and P_{CO2}), and electrolyte composition. Alternatively, engineered microorganisms, or a two-step process combining MES to fermentation with an added electron donor, are viable strategies to produce high-value chemicals.

and hexanol have been the focus of recent research initiatives (Vassilev et al., 2018). Butanol can be directly incorporated in the current fuel infrastructure, whereas hexanol, besides being an alternative to petrol-derived gasoline, has multiple end-uses in the pharmaceutical, cosmetic, textile, food (both as pesticide and flavouring agent), and leather industry (Fernández-Naveira et al., 2017).

MES has the potential for meeting the future demand of the chemical industry, but further research is required to achieve production costs comparable to the currently applied chemical synthesis. Furthermore, despite the efforts aimed at understanding the metabolic pathways governing MES, and how they are affected by the operation conditions (Blasco-Gómez et al., 2019; Vassilev et al., 2018), a replicable, robust strategy for the selective production of carboxylate molecules other than acetic acid has not yet been developed.

4. Downstream processing

Downstream processing of MES products, including extraction, fractionation, concentration and purification, can account for more than 60% of the production cost (Prévoteau et al., 2020). Thus, development of a cost-effective extraction and separation method is crucial to achieve large-scale production of bio-based chemicals. Several extraction techniques have been proposed for extraction and separation of typical MES products, such as C2-C6 monocarboxylic acids (Table 3), described in the following sections.

4.1. Conventional separation processes

Conventional processes widely investigated for separation of organic acids are adsorption and liquid-liquid extraction (LLE). Adsorption is based on the ion exchange between carboxylate groups and functionalized solid sorbents, *e.g.* amine-based anion exchange resins (Rebecchi et al., 2016; Reyhanitash et al., 2017). In most cases, the performance of the sorbent depends on the pH of the solution. High adsorption capacities are achieved at intermediate pH values (~6.5), since an increasing pH causes an increasing concentration of acid in ionized form, but also a reduction of the amine concentration in protonated form (Rebecchi et al., 2016).

LLE is also a well-studied technology for separation of organic acids (Alkaya et al., 2009; Reyhanitash et al., 2016). Organophosphates such as tri-n-octylphosphine oxide (TOPO), tri-n-butyl phosphate and aliphatic amines have been identified as the most suitable extractants. Alkaya et al. (2009) used TOPO in kerosene to recover VFAs from a fermentation broth of sugar beet processing waste, reaching VFA recoveries of 61–98%, where the efficiency increases with increasing TOPO concentration (up to 20 wt%).

4.2. Concentration-driven and pressure-driven membrane processes

Pertraction is a membrane process where an organic solvent is immobilized (by capillary forces) inside the pores of a hydrophobic microfiltration membrane, thus separating the feed from the permeate (Dzygiel and Wieczorek, 2010). Organic compounds from the feed diffuse through the organic solvent in the membrane and can be continuously back-extracted on the permeate side. The membrane only acts as mechanical support, thus the extraction selectivity relies only on the extractant. Pertraction has been widely adopted for VFA extraction (Table 3), since it has several advantages compared to conventional LLE, such as (i) small amounts of organic solvent required, (ii) simultaneous extraction and solvent stripping, and (iii) lower operational costs. When

Table 3
Main investigated technologies for extraction and separation of organic acids from fermentation broths.

Technology	TRL^{a}	Advantages	Disadvantages	References
Conventional separation processes				
Adsorption in ion exchange resins	Industrial	Low CAPEX^{b}; no pretreatment needed	Ion-exchange influenced by pH	Bajracharya et al. (2017b); Rebecchi et al. (2016); Reyhanitash et al. (2017); Saito et al. (2009)
Liquid–liquid extraction	Industrial	High extraction efficiency	High OPEX^{c} (compared to pertraction) and large use of extractant	Alkaya et al. (2009); Bekatorou et al. (2016); Reyhanitash et al. (2016); Saboe et al. (2018)
Concentration-driven and pressure-driven membrane processes				
Pertraction (membrane liquid-liquid extraction)	Industrial	High extraction efficiency; low OPEX; selective extraction possible (based on hydrophobicity)	Selectivity depends on solvent	Agler et al. (2012); Aydin et al. (2018); Batlle-Vilanova et al. (2017); Dessì et al. (2020); Nuchnoi et al. (1987); Outram and Zhang (2018); Plácido and Zhang (2018); Yesil et al. (2014)
Pervaporation	Lab	Simultaneous extraction and liquid-vapour phase change	Loss of extractant *via* evaporation; selectivity depends on permeate pressure (high vacuum needed)	Choudhari et al. (2015); Qin et al. (2003)
Nanofiltration	Industrial	Low CAPEX/OPEX; high rejection of high-molecular weight solutes	Separation strongly affected by pH and electrostatic interactions with membrane	Cho et al. (2012); Xiong et al. (2015); Zacharof et al. (2016)
Forward osmosis	Demo	High rejection of organics	Membrane biofouling and VFA degradation; rejection rates dependent on availability and concentration of draw solution	Blandin et al. (2019); Cho et al. (2012)
Electro-membrane processes				
Electrodialysis (ED)	Industrial	Low OPEX; easily scalable	Low selectivity among carboxylates and other anions	Cerrillo et al. (2016); Jones et al. (2017, 2015); Scoma et al. (2016); Zhang and Angelidaki (2015)
Membrane electrolysis	Industrial	Reduced chemical dosage thanks to in-situ production of H^{+}/OH^{-}	Membrane fouling; less easily scalable than ED (because of non-modular unit)	Gildemyn et al. (2015); Xu et al. (2015)
Electrodeionization (EDI)	Industrial	Possibility to treat very diluted streams; reduced energy consumption	Higher pressure drops and fouling tendency (compared to ED)	Lopez and Hestekin (2015)
Bipolar electrodialysis (BMED)	Lab/ demo	Reduced chemical dosage thanks to in-situ production of H^{+}/OH^{-}	No selectivity for a specific organic acid; higher membrane costs (compared to ED)	Arslan et al. (2017); Shi et al. (2018); Xue et al. (2017)
Reactive extraction processes				
Reactive extraction with ionic liquids	Lab	Simultaneous extraction and esterification	High costs of ionic liquids with good extraction properties; ionic liquid losses	Andersen et al. (2016)
Reactive extraction in supercritical CO_2	Lab	Higher partition coefficient than physical extraction	Product losses due to formation of acid-amine complexes	Djas and Henczka (2018); Henczka and Djas (2016)

[a] Technology readiness level; [b] Capital expenditures; [c] Operational expenditures.

using hollow fibre membranes, the organic phase is typically fed on the shell side and the aqueous feed on the tube side, although the opposite configuration could result in higher mass transfer rates (Pabby and Sastre, 2013). Recently, the use of silicone membranes has also been proposed, with water as extractant, showing good selectivity towards VFAs based on hydrophobicity (isovaleric > butyric > acetic) (Outram and Zhang, 2018). A silicone membrane was applied *in-line* to a cheese whey fermentation process by Dessì et al. (2020), achieving selective extraction of butyric acid over propionic and acetic acid. However, low pH (as close as possible to carboxylic acid pK_a) is required, since only undissociated acids can be extracted. The process was also shown suitable for alcohol extraction, whereas nutrients were retained, highlighting its potential for *in-line* product extraction from the MES catholyte.

In pervaporation, the target compounds are extracted *via* partial vaporization through a membrane, by maintaining the permeate side under vacuum. The extractant must have high boiling point, low viscosity, and low solubility in water, and the most used extractants are high-molecular-weight alkyl amines such as trioctylamine (TOA), trilaurylamine (TLA), and tri-n-octylphosphine oxide (TOPO) (Nuchnoi et al., 1987; Qin et al., 2003).

Nanofiltration (NF) has been also widely investigated for VFA separation. Xiong et al. (2015) used commercial NF membranes to separate organic acids in lignocellulosic biomass digestion liquors, achieving 86% recovery (except for butyric acid, likely due to interactions with other components in the digestion liquor). In NF, the pH affects both the surface charge of the membrane and the degree of ionization of the acids. Acetic acid rejection increased from 0 to 62% with pH increase from 3 to 7 (Xiong et al., 2015), since at high pH the membrane (negatively charged) rejects carboxylate ions due to electrostatic effects. Therefore, low pH (in the range of 2.9-3.0) is advantageous for acetic acid separation via NF (Cho et al., 2012), which could preclude its *in-line* application to MES.

Forward osmosis (FO) exploits the osmotic pressure difference between the feed and a draw solution kept at the same hydrostatic pressure. The process efficiency, fouling and energy consumption are strongly influenced by the composition and concentration of the draw solution. Blandin et al. (2019) used FO to concentrate VFAs (mainly acetic acid) from domestic wastewater, achieving rejection rates >80% at pH 7.5. At pH 4, instead, the rejection drastically decreased, since the separation becomes mostly steric for undissociated acids (*i.e.*, small molecules such as acetic acid can pass through the FO membrane, while larger molecules are rejected), thus showing the possibility to achieve selective separation. Rejection is also affected by molecule geometry (*e.g.*, n-butyric acid shows higher rejection than iso-butyric acid), hydrophilicity, electrostatic and specific solute-membrane interactions. In general, anti-fouling strategies (*e.g.* backwashing) are crucial to limit VFA biodegradation on the membrane surface.

4.3. *Electro-membrane processes*

Electrodialysis (ED) is the most widely applied electro-membrane technology at industrial scale, and has also been widely investigated for organic acid recovery (Huang et al., 2007). Jones et al. (2017, 2015) achieved up to 99% VFA recovery from hydrogen fermentation broths, and also demonstrated the use of ED for *in-line* VFA extraction. However, ED suffers from low selectivity towards organic acids, and other anions (such as Cl^-) are also inevitably extracted, especially if present at high concentration (Scoma et al., 2016).

Membrane electrolysis is an ED-based technology where anode and cathode play a crucial role in the process by producing H^+ and OH^- (Xu et al., 2015). Membrane electrolysis has been applied (in combination to pertraction) to selectively extract caproic acid from a fermentation broth, in which a pH gradient between the two chambers was electrochemically maintained, without chemicals addition (Xu et al., 2015).

Another alternative is bipolar membrane electrodialysis (BMED), *i.e.* an ED-like system that contains a bipolar membrane to promote water dissociation into H^+ and OH^- *via* a catalysed protonation-deprotonation mechanism. The main advantage of BMED is the *in-situ* production of H^+ and OH^- on the membrane surface, thus allowing pH change in the cell without dosing chemicals. BMED has been proposed for simultaneous electrochemical production and recovery of acetic acid (Zhang et al., 2011) and propionic acid (Boyaval et al., 1993).

A possible strategy to further enhance the separation efficiency is to use electrodeionisation (EDI), *i.e.*, an ED-like system where the compartments are filled with ion exchange material (*e.g.* beads or wafers), to enhance ion transport in dilute stream conditions. Lopez and Hestekin (2015) used an EDI cell with ion exchange wafer and ionic liquids to remove butyrate and acetate from a synthetic fermentation broth, showing current efficiency up to 90% and energy consumptions of 1.25-2.80 kWh/kg acid recovered.

4.4. *Reactive extraction processes*

Ionic liquids (ILs) have been investigated for selective extraction of organic acids. Andersen et al. (2016) used ILs for the simultaneous concentration and esterification of MES-produced acetic acid (extracted *via* membrane electrolysis). Acetic acid was concentrated up to 80 mM using a bis(trifluoromethylsulfonyl)-imide IL, followed by esterification to ethyl acetate, upon ethanol addition, with a maximum conversion of 90%. This proof-of-concept study opens opportunities for widening the product spectrum of MES.

Another proposed strategy to recovery VFAs is the reactive extraction using organic solvents in supercritical CO_2 (Djas and Henczka, 2018). Henczka and Djas (2016) investigated the reactive extraction of acetic and propionic acid (0.07-1.04 M) using TOA in supercritical CO_2 (at 35-65°C and 80-160 bar), reaching a highest extraction efficiency of 94.7% for propionic acid, although part of the product was lost due to the formation of acid-amine complexes. Both pressure and temperature significantly influence the separation efficiency, due to the effect on the density and solvating power of supercritical CO_2.

4.5. *Perspectives for integrated MES-VFA extraction systems*

Achieving selective separation of VFAs from dilute aqueous streams is still one of the biggest challenges for upscaling VFA biological production. The separation selectivity is influenced by several factors, such as pH, mobility, hydrophobicity, molecular weight, and ionization degree of the target product (Moon et al., 1998). This is especially challenging in MES, due to the low product concentration. For instance, MES reactors can only produce up to 7–10 g/L acetate, due to product inhibition (Bajracharya et al., 2017c). These concentrations are not yet sufficient for economically upscaling if compared to industrial fermentation processes, where concentrations of 20–200 g/L of organic acids can be achieved (López-Garzón and Straathof, 2014). In this regard, the maximisation of MES production rates is strictly linked to the development of an efficient *in-situ* extraction system, to minimise product degradation and alleviate the inhibition caused by the end-product accumulation (Batlle-Vilanova et al., 2017).

Since both extraction and concentration of VFAs are pH-dependent processes, an efficient pH control is of outmost importance to minimize the operational costs. In this regard, technologies that can provide *in-situ* production of H^+ and OH^- (such as BMED, or membrane electrolysis) are advantageous to reduce the chemical dosage for pH control. For membrane-based extraction processes, one of the challenges in process integration with MES is preventing fouling. Pretreatment of the fermentation broths is required to remove suspended solids and colloids that can cause fouling, and tailored membrane with anti-fouling properties and increased selectivity toward organic anions should be designed. Since ED-based technologies suffer of low selectivity towards the target products, they can be deployed as final concentration step after extraction using membrane technologies with higher selective extraction capabilities, such as pertraction, forward osmosis, or pervaporation (especially in the case of VFAs).

Very limited information is available in literature on capital and operation costs for VFA purification, which depend on the maturity and market of the separation technology, and on the economy of scale of the MES process. Jourdin et al. (2020) estimated a capital cost of 1000 €/ton, and an operation cost of 344 €/ton for the separation of caproic acid produced as the sole product in a MES cell. However, such rough estimation did not take into account the economy of scale factor, and costs will inevitably increase when separating specific products from mixtures of organic compounds, which appears as a more realistic scenario with the current state-of-art MES technology.

5. Development of sustainable MES biorefineries

5.1. Renewable energy sources to power MES

Electric energy is a major cost for (bio)electrochemical processes. When assuming an optimistic CE of 90% and an operational voltage of 3 V, it was estimated that about 12 kWh_{el} are necessary for producing 1 kg of acetic acid, and such power consumption nearly doubles for producing caproic acid (Prévoteau et al., 2020). Considering the current average price of 69 €/MWh (Child et al., 2019), the electricity cost for producing 1 kg of acetic acid (0.83 €) is already higher than its commercial value, without taking into account operational, maintenance and downstream processing costs. Furthermore, if powered with fossil fuel-based energy, MES could cause a net generation, rather than mitigation, of carbon emissions (Christodoulou et al., 2017). Thus, the use of renewable, low-cost energy is a crucial strategic factor for sustainable MES biorefineries. Renewable energy capacity in EU increased from 258 to 512 GWe over the period 2007–2017, with an exceptional growth of solar photovoltaics (+1966%), offshore wind (+1365%), onshore wind (+180%) and bioenergy (+94%). The adoption of renewable energy is forecasted to push down the electricity price by 20-30% at least, increasing competitiveness with fossil-fuel-based energy (Child et al., 2019).

Renewable energy sources can be integrated into MES either indirectly, by using renewable electric energy produced from solar, wind, geothermal, hydro or biomasses to power MES, or directly, by solar-to-product conversion using photoactive electrodes producing the required power density (Fig. 7). The indirect approach appears particularly convenient for storing the low-cost excess power produced by the inherently fluctuating renewable sources as multi-carbon chemicals (Patil et al., 2015). However, fluctuating electric supply could temporarily decrease the production rates in MES, or even shift the metabolic pathway from carboxylic acid to methane production (Mateos et al., 2020). Such an issue can be avoided by using batteries and dedicated electronic circuits to deliver a constant current to the MES reactor (more details in Section 5.3).

The direct approach entails the key advantage of being independent of an electricity source (Bushuyev et al., 2018). However, photo-MES cells must be equipped with a power storage unit (see section 5.3) or light emitting diodes (LEDs) to ensure a continuous current delivery to the cathode. In the last decade, photoelectrochemical cells for water splitting have been technologically advanced, and are currently capable to deliver sufficient currents (up-to 5.8 mA/cm^2) to drive electrochemical CO_2 reduction (Kirner and Finke, 2017). Hybrid systems, with biological cathodes coupled to photoelectrochemical anodes, have been thus demonstrated for self-sustained methane, isopropanol or acetic acid production from CO_2 (Table 4). An average solar conversion efficiency (SCE) of 0.62%, about three times higher than the global natural photosynthesis, was achieved for biological conversion of CO_2 to methane deploying the reducing current generated by a TiO_2 CdS photoanode (Xiao et al., 2020). Methane was generated at the cathode with a production rate of 15 $L/(m^2 \cdot d)$, which further increased to 20.8 $L/(m^2 \cdot d)$ (0.86% SCE) when a Cu_2ZnSnS_4 light adsorbing sensitiser was

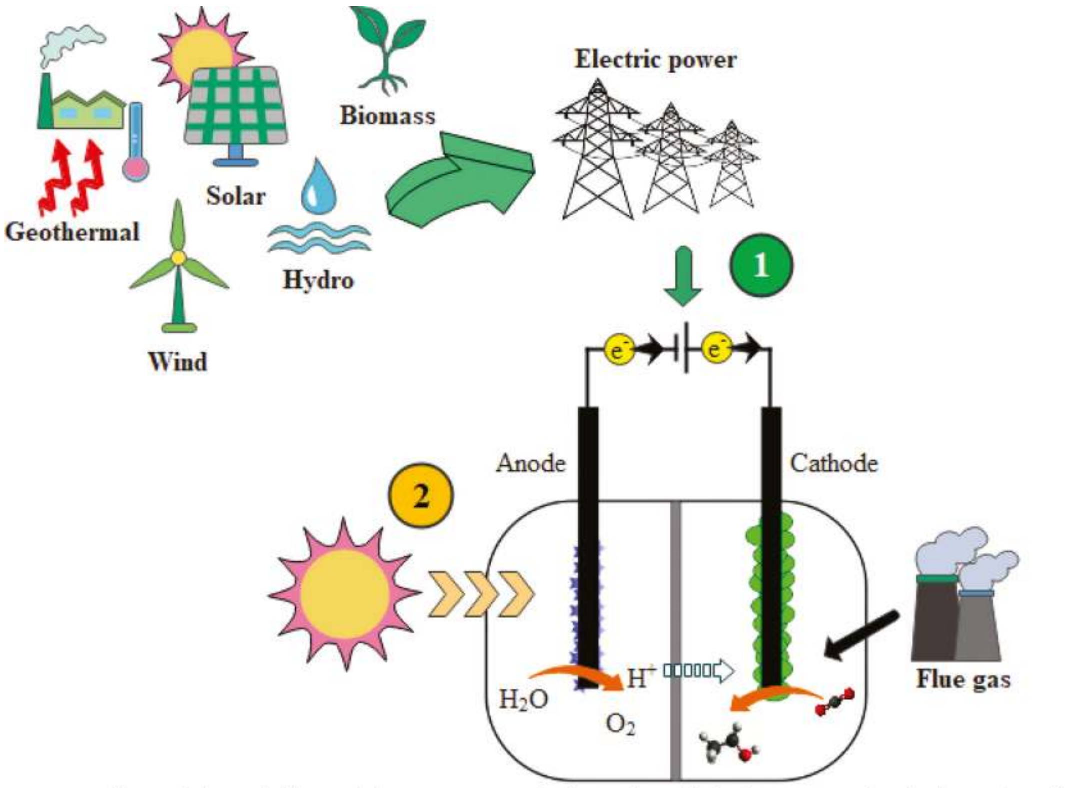

Fig. 7. Indirect (1) and direct (2) power supply for microbial electrosynthesis (MES) cells. In the indirect approach, electric energy is generated from renewable sources and then used to drive water splitting (at the anode) and CO_2 bio-electrochemical reduction (at the cathode). In the direct approach, water oxidation is obtained from solar energy using a photoanode.

Table 4

Hybrid systems combining biocathode and photoanode for self-sustained CO_2 recycling. The photocatalytic current, main product, coulombic efficiency (CE) and solar conversion efficiency (SCE) are reported. In all studies, the photoanode was exposed to a light intensity of 100 mW/cm^2.

Inoculum	Cell design	Cathode	Anode	Current (mA/cm^2)	Main product (yield/final concentration)	CE (%)	SCE (%)	Reference
Engineered *Ralstonia eutropha*	One-chamber	NiMoZn or stainless steel	CoP_i	0.5-1.1	Isopropanol (216 mg/L)	3.9	0.7	Torella et al. (2015)
Enriched methanogenic community	Two-chamber	Carbon cloth	TiO_2 nanowire array	0.07-0.09	Methane (1.92 L/(m^2•d))	95	0.1	Fu et al. (2018)
Sporomusa ovata	Two-chamber	Si and TiO_2 nanowires arrays	TiO_2 nanowires	0.3	Acetic acid (6 g/L)	86	0.38	Liu et al. (2015)
Effluent from methanogenic MES	Two-chamber	Chitosan-modified carbon cloth	TiO_2/CdS on FTO[a] (with CZTS[b] sensitiser)	0.6	Methane (15 L/(m^2•d), 20.8 L/(m^2•d) with CZTS)	93	0.62 (0.86 with CZTS)	Xiao et al. (2020)

[a] Fluorine-doped tin oxide; [b] Copper zinc tin sulphide.

added to the photoanode. Liu et al. (2015) reported acetic acid concentrations as high as 6 g/L in a hybrid system with *Sporomusa ovata* and TiO_2 nanowires as the bio- and photocatalyst, respectively, which is comparable to the concentrations achieved in conventional MES cells (Prévoteau et al., 2020). Enzymatic biocathodes have been also employed for CO_2 reduction (Lee et al., 2016), although the high production and operation costs of enzymatic electrodes, requiring periodic regeneration, discourages their use in full-scale MES applications.

5.2. Integrated MES devices for CO_2 recycling and wastewater treatment

When CO_2 reduction at the cathode is coupled to water oxidation at the anode, high potentials or expensive catalysts are required to obtain the oxygen evolution reaction (Bian et al., 2020). Furthermore, a share of the oxygen produced at the anode can diffuse towards the cathode inhibiting the strictly anaerobic microorganisms. An integrated process combining CO_2 reduction at the cathode and oxidation of pollutants at the anode not only will decrease the energy demand of MES, but will also simultaneously address two major challenges faced by industries (reduction of CO_2 emissions and wastewater treatment). A maximum acetic acid production rate of 83 mg/(m^3•d) was reported for a biocathode at a current density of 0.04 mA/cm^2 generated by a bioanode fed with synthetic wastewater containing 4 g/L sodium acetate. The COD removal rate reached 87% at a relatively low cell potential of 1.4 V (Xiang et al., 2017). Furthermore, acetic acid production from CO_2 was demonstrated at potentials as low as 0.8 V though with a corresponding decrease in production rate. In addition, CO_2 produced from wastewater treatment at the anode can be recycled to the cathodic chamber and act as a precursor for chemical production (Zhao et al., 2012). Photocatalytic oxidation can also be exploited for selective oxidation of target compounds such as alkenes (Farràs et al., 2015). However, optimisation of both the cathodic and anodic reaction in integrated systems can be difficult, and further studies involving real wastewaters are required to assess the feasibility of this approach.

5.3. Energy storage and smart electronic design for MES

Although MES reactors demonstrated their resiliencies to current fluctuations, a constant electricity supply is required for a robust 24/7 operation. Thus, when fluctuating energy sources are used to power MES, additional investment is required for energy storage systems to recover excessive energy from the production peaks and deliver it to the MES reactors at a constant flow. The price of storage technologies, batteries in particular, decreased by 60% in the past five years, approaching the threshold of 100 €/kWh (Berckmans et al., 2017). Power storage costs of 0.085 €/kWh have been estimated in Germany for 7 hours storage duration, low enough to incentivise the installation of batteries for harvesting solar power, and projected to further decrease to 0.065 €/kWh within four years (Comello and Reichelstein, 2019). As an alternative, MFCs treating wastewater can be used to produce electric energy for charging energy storage devices, which are subsequently discharged to power MES reactors (Hatzell et al., 2013).

In MES stacks, even if the cells are connected in parallel, the potential control is more challenging than in purely electrochemical electrolysers. The inherently inhomogeneous microbial catalysts can indeed cause non-uniform charge distribution on the MES electrodes. This creates uneven potentials between the cells in the stack, that may cause a shift of the microbial communities (when mixed culture are used) or metabolic pathways underpinning CO_2 recycling (Sánchez et al., 2020). Balancing charge distribution in MES stacks could find inspiration in power management systems (PMS) already available in battery stacks. PMS are capable of detecting overvoltage and overloading, switching off the connection to prolong the lifespan, and reducing stress on battery units (Stroe et al., 2018). Similarly, MES could use smart electronics to optimise voltage or current delivery (Fig. 8), allowing a stable chemical output. Such switching systems have already been implemented to improve the energy output in MFC grids (Kim et al., 2011). Potentiostatic cell control is costly, but enables a precise electrode potential control that allows to operate the cells under optimal conditions. Galvanostatic control is cheaper, but can result in fluctuations and divergence among the cells.

6. Outlook and future perspectives

The environmental incentives and increasing CO_2 emission costs as carbon taxes are pushing industries towards the use of carbon conversion technologies. Although CCS technologies are already available at commercial scale, the emerging CCU technologies such as MES have the potential to gradually replace the existing chemical production facilities, producing a revenue stream that can offset the operation costs (Grim et al., 2020). When coupled to renewable energy, electrochemical CO_2 conversion technologies can produce chemicals with a negative carbon footprint (De Luna et al., 2019), and their development is further incentivised by the decreasing electric energy cost. MES is a flexible technology with several market entry opportunities and potentially applicable to decarbonise industrial CO_2-containing flue gas while producing fuels and chemicals that find application in the packaging, food, preservatives, rubber, metallurgy, pharmacy, polymers, chemical and renewable energy industry (ElMekawy et al., 2016).

Various platform chemicals and fuels can be produced in MES, raising argument about which products are the most viable from an economic perspective. Though a rough estimation on the techno-economic viability of different MES routes can be obtained with thermodynamic calculations, more in-depth techno-economic analyses are required. However, to date, no results on scaled-up MES reactors and operation under relevant conditions are available to support techno-economic analyses. Up to now, acetic acid is the only chemical that is produced in MES with selectivity >90%, and substantially higher rates than other chemicals (>100 g/(m^2•d)), and has thus the highest decarbonisation potential (Jiang et al., 2019). Furthermore, acetic acid

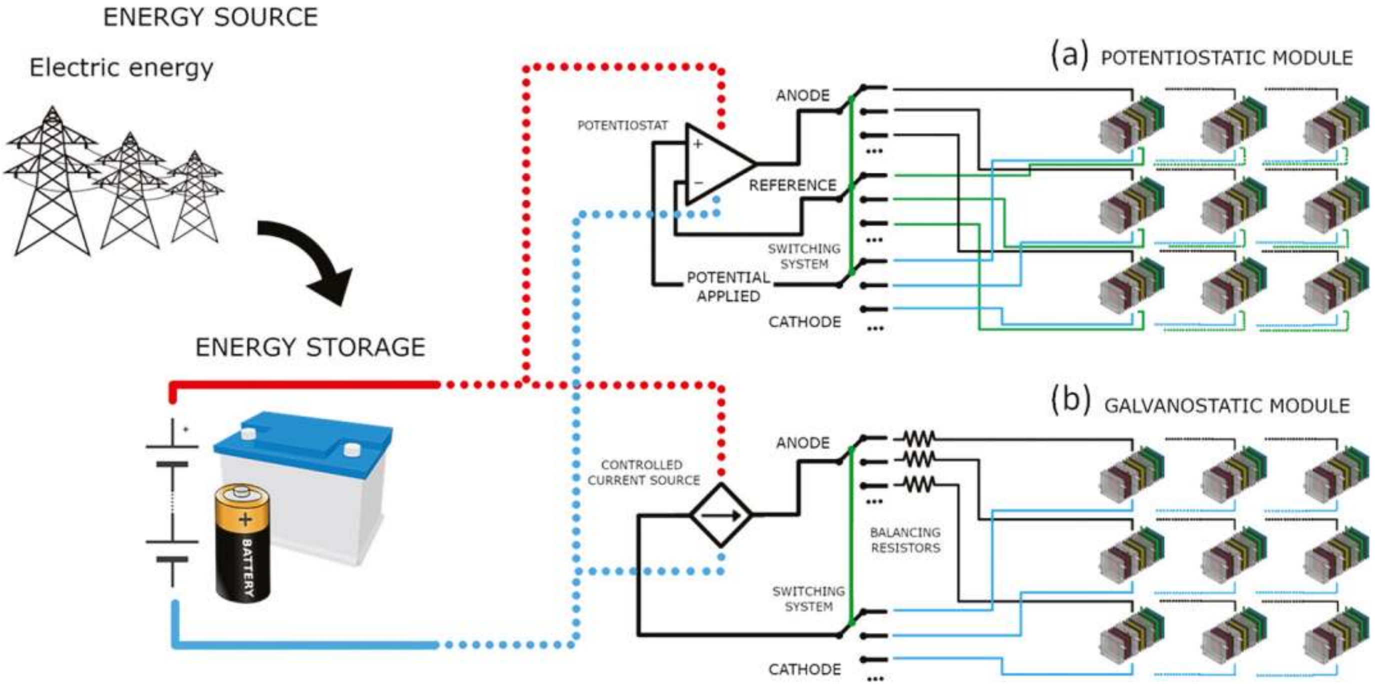

Fig. 8. Example of application of power managing system and smart electronics for potential or current control in MES stacks. (a) Each stack shares the same potential control amplifier which allows potential control in each cell through a multiplexer. (b) The cells are controlled in galvanostatic mode, and balancing resistors are connected in series to minimise differences among the cells. In case of failure, a stack can be switched off for maintenance without affecting the other stacks.

has a huge market size of about 13 Mtons/year and can be used as a precursor for many valuable products. As such, it currently represents one of the most compelling targets. However, the economic viability of acetic acid production in MES is limited by its low market value (Christodoulou et al., 2017). Thus, research efforts are currently directed towards the selective production of more valuable compounds with reasonably high production rates. The main ongoing European research projects dealing with bio-electro CO_2 recycling, such as Bio-RECO2VER, SCALIBUR, BIOCON-CO_2, BAC-TO-FUEL, and Celbicon, are making a step beyond in demonstrating the technical feasibility for the production platform of valuable biochemicals and biocommodities (*e.g.* isobutene, lactic acid, biofuels, biopolymers, and surfactants). This is in line with the European strategy of seeking renewable fuels with high energy densities and low hygroscopicity, to be blended, or even to replace, fossil-based fuels for direct use in engines. Hybrid systems, in which enzymes or genetically modified organisms are applied to produce high-value compounds from electrochemically-produced building blocks, is another emerging field that is expected to play a key role in the future of CO_2 recycling (Bushuyev et al., 2018).

Besides commercial purposes, MES-derived chemicals can find application within the same industry they are produced. Such approach can decrease the costs of infrastructure required for product purification and transportation. For example, MES can be applied in existing power plants, as renewable energy storage during peak production, or in wastewater treatment plants, to convert CO_2 into organic substrates for processes such as denitrification (Osset-Álvarez et al., 2019). MES can also be seen as part of a biorefinery aiming at cleaning wastewater at the anode while upgrading biogas into biomethane at the cathode and recycling the resulting CO_2 to produce further methane, or for other purposes (Sadhukhan et al., 2016). Similarly, MES can provide reducing equivalents for syngas fermentation (Zhang and Tremblay, 2019). Biofuels produced from CO_2 can be used within the company as an alternative fuel for boilers, combined heat and power (CHP) plants and transportation. Integration of MES into bioethanol production plants would help increase the energetic efficiency of the whole process by recycling energy that is initially lost in the liquid waste, and increase the ethanol yield by recycling the CO_2 produced by solventogenic fermentation. Electrosynthesis products such as H_2, CH_4, CO and VFAs can be further upgraded to longer chain carboxylates, biofuels, bioplastics, polysaccharides and protein *via* multi-step bioconversions (Bian et al., 2020; Haas et al., 2018), or even in the same MES cell (Vassilev et al., 2019).

To date, most research interest in MES has been directed towards cathodic products, whereas anodic reactions have been overlooked. It was estimated that the anode, particularly when coated with expensive catalysts such as Pt, can generate as high as 59% of the capital costs (Jourdin et al., 2020). However, several value-added products can be obtained through oxidative reactions at the anode (Fig. 9), which could complement biocathodic products to increase the economic sustainability of MES. As an example, a relatively pure oxygen stream is generated by water oxidation at the anode, which can find a plethora of application in the chemical and manufacturing industry, as well as in waste and wastewater treatment facilities. Anodic reactions can be also exploited for producing disinfectants such as chlorine (Batlle-Vilanova et al., 2019), or ozone (Yan et al., 2020), although particular care should be given to prevent their cross-over to the biocathode. Oxidation reactions at the anode can also be applied for resource recovery. Hydrogen sulphide has been proposed as an electron donor in a MES for concomitant acetic acid production from CO_2, and sulphur/sulphate formation (Gong et al., 2013). Such process could be applied to sulphide-containing flue gas, allowing sulphur/sulphate recovery at the anode while reducing the power required for CO_2 reduction at the cathode in comparison to water oxidation. However, biological anodic processes, in particular when heterotrophic microorganisms are present, can result in a higher risk of membrane biofouling in comparison of MES cells where only the cathodic process is biological. Finally, the anodic process can be potentially applied to upgrade MES products (*i.e.* carboxylic acids), *e.g.* to octane *via* Kolbe electrolysis (Stang and Harnisch, 2016).

In summary, several challenges need to be overcome to push MES technology towards industrial adoption. Further research efforts are

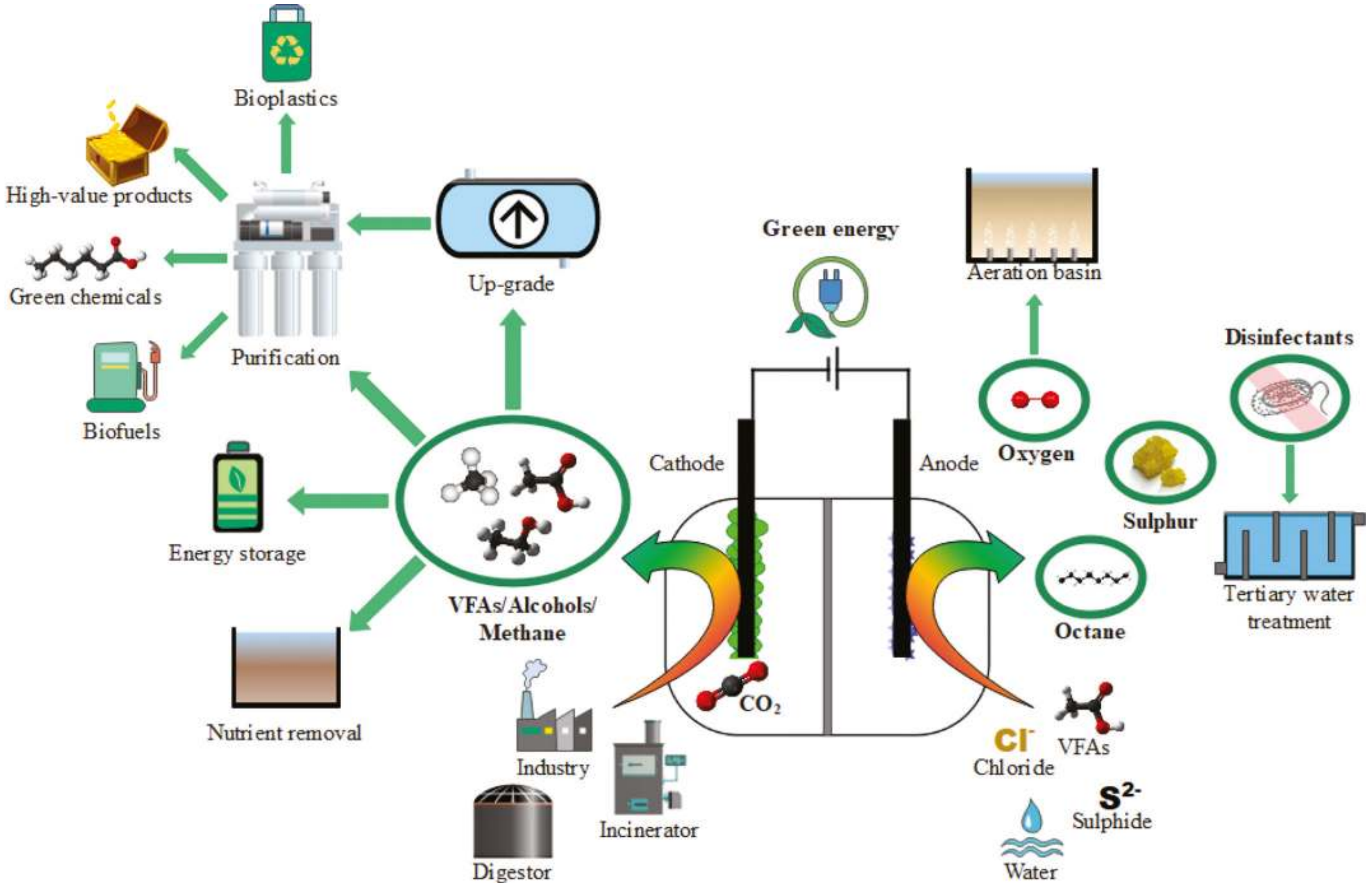

Fig. 9. Integration of cathodic and anodic processes in MES. CO_2 is biologically converted into short-chain fatty acids, alcohols or methane. Such products can be used as energy storage, or purified for use in the chemical industry or as biofuel, or up-graded into bioplastics or other high-value products. Anodic reactions can be exploited to produce useful chemical such as oxygen and disinfectants for application in water treatment, for sulphur recovery from sulphide, or to upgrade carboxylic acids to octane *via* Kolbe electrolysis.

required to decrease the capital costs associated to carbon capture and cell materials (in particular the anode electrode). Increasing the production rates, and developing strategies to selectively produce and extract high-value products, can boost the economic viability of the process. Powering the MES stack with renewable electricity is essential to ensure carbon-neutrality, and more attention is required to the anodic reaction to reduce current consumption, possibly generating a secondary revenue stream. MES technology is approaching the maturity level required to finally overstep the laboratory, and operation of pilot plants under relevant industrial conditions will corroborate its techno-economic feasibility.

7. Conclusions

MES has shown potential for replacing fossil-fuel based synthesis of platform chemicals or energy products, and significant opportunities for its establishment are yet to arise in response to the stringent legislation on carbon emissions and the decreasing cost of electric energy. The flexibility of MES, applicable to convert CO_2 containing gas from different sources to a plethora of different chemical products, can represent a key differentiator to enter the market. However, significant challenges need to be tackled before commercialisation. MES stacks need to be designed and operated under relevant condition (*e.g.* in pilot scale) to assess the technology from a techno-economic point of view. Efficient *in-line* product extraction and purification, as well as valorisation of the anodic reaction to obtain further commercial or commodity products, are key aspects in this regard. Since decarbonising the energy and the production sector is a priority, abatement of high CO_2 loads, even if producing low-value compounds such as acetic acid, appears as the most feasible approach for commercialising MES in the short term.

Acknowledgements

This work was performed on the framework of the Science Foundation Ireland (SFI) Pathfinder Award on “Hybrid Bio-Solar Reactors for wastewater treatment and CO_2 recycling” (award nr. 19/FIP/ZE/7572PF). L.R.-A. and S.P. thank the European Union’s Horizon 2020 research and innovation program under the grant agreement No 760431 (BIORECO2VER), the Agency for Business Competitiveness of the Government of Catalonia (ACCIÓ; COMRDI16-1-0061) and Spanish Ministry of Science (RTI2018-098360-B-I00). L.R.-A. acknowledge the support by the Catalan Government (2018 FI-B 00347) in the European FSE program (CCI 2014ES05SFOP007). S.P. is a Serra Húnter Fellow (UdG-AG-575) and acknowledges the funding from the ICREA Acadèmia award. LEQUiA has been recognized as consolidated research group by the Catalan Government with code 2017-SGR-1552. W.T. and P.F. acknowledge financial support from INTERREG Atlantic Area programme (Grant reference EAPA_190_2016), and P.F. acknowledges support from Royal Society Alumni programme. M.T. and H.V.M.H. acknowledge the financial support of Wetsus co-funders, *i.e.* the Dutch Ministry of Economic Affairs and Ministry of Infrastructure and Environment, the Province of Fryslân, and the Northern Netherlands Provinces. P.C. acknowledges funding received from SERB, Govt. of India funded project (Grant Reference SRG/2019/00075).

References

Agler, M.T., Spirito, C.M., Usack, J.G., Werner, J.J., Angenent, L.T., 2012. Chain elongation with reactor microbiomes: Upgrading dilute ethanol to medium-chain carboxylates. Energy Environ. Sci. 5, 8189–8192. https://doi.org/10.1039/c2ee22101b.

Alkaya, E., Kaptan, S., Ozkan, L., Uludag-Demirer, S., Demirer, G.N., 2009. Recovery of acids from anaerobic acidification broth by liquid-liquid extraction. Chemosphere 77, 1137–1142. https://doi.org/10.1016/j.chemosphere.2009.08.027.

Andersen, S.J., Berton, J.K.E.T., Naert, P., Gildemyn, S., Rabaey, K., Stevens, C. V, 2016. Extraction and esterification of low-titer short-chain volatile fatty acids from anaerobic fermentation with ionic liquids. ChemSusChem 9, 2059–2063. doi: https://doi.org/10.1002/cssc.201600473.

Aouini, I., Ledoux, A., Estel, L., Mary, S., 2014. Pilot plant studies for CO$_2$ capture from waste incinerator flue gas using MEA based solvent. Oil Gas Sci. Technol. 69, 1091–1104. https://doi.org/10.2516/ogst/2013205.

Arends, J.B.A., Patil, S.A., Roume, H., Rabaey, K., 2017. Continuous long-term electricity-driven bioproduction of carboxylates and isopropanol from CO$_2$ with a mixed microbial community. J. CO$_2$ Util. 20, 141–149. https://doi.org/10.1016/j.jcou.2017.04.014.

Aresta, M., Dibenedetto, A., Angelini, A., 2013. The changing paradigm in CO$_2$ utilization. J. CO$_2$ Util. 3–4, 65–73. https://doi.org/10.1016/j.jcou.2013.08.001.

Arslan, D., Zhang, Y., Steinbusch, K.J.J., Diels, L., Hamelers, H.V.M., Buisman, C.J.N., De Wever, H., 2017. In-situ carboxylate recovery and simultaneous pH control with tailor- config.d bipolar membrane electrodialysis during continuous mixed culture fermentation. Sep. Purif. Technol. 175, 27–35. https://doi.org/10.1016/j.seppur.2016.11.032.

Aydin, S., Yesil, H., Tugtas, A.E., 2018. Recovery of mixed volatile fatty acids from anaerobically fermented organic wastes by vapor permeation membrane contactors. Bioresour. Technol. 250, 548–555. https://doi.org/10.1016/j.biortech.2017.11.061.

Bains, P., Psarras, P., Wilcox, J., 2017. CO$_2$ capture from the industry sector. Prog. Energy Combust. Sci. 63, 146–172. doi:https://doi.org/10.1016/j.pecs.2017.07.001.

Bajracharya, S., Vanbroekhoven, K., Buisman, C.J.N., Pant, D., Strik, D.P.B.T.B., 2016. Application of gas diffusion biocathode in microbial electrosynthesis from carbon dioxide. Environ. Sci. Pollut. Res. 23, 22292–22308. https://doi.org/10.1007/s11356-016-7196-x.

Bajracharya, S., Srikanth, S., Mohanakrishna, G., Zacharia, R., Strik, D.P., Pant, D., 2017a. Biotransformation of carbon dioxide in bioelectrochemical systems: State of the art and future prospects. J. Power Sources 356, 256–273. https://doi.org/10.1016/j.jpowsour.2017.04.024.

Bajracharya, S., van den Burg, B., Vanbroekhoven, K., De Wever, H., Buisman, C.J.N., Pant, D., Strik, D.P.B.T.B., 2017b. *In situ* acetate separation in microbial electrosynthesis from CO$_2$ using ion-exchange resin. Electrochim. Acta 237, 267–275. https://doi.org/10.1016/j.electacta.2017.03.209.

Bajracharya, S., Yuliasni, R., Vanbroekhoven, K., Buisman, C.J.N., Strik, D.P.B.T.B., Pant, D., 2017c. Long-term operation of microbial electrosynthesis cell reducing CO$_2$ to multi-carbon chemicals with a mixed culture avoiding methanogenesis. Bioelectrochemistry 113, 26–34. https://doi.org/10.1016/j.bioelechem.2016.09.001.

Batlle-Vilanova, P., Ganigué, R., Ramió-Pujol, S., Bañeras, L., Jiménez, G., Hidalgo, M., Balaguer, M.D., Colprim, J., Puig, S., 2017. Microbial electrosynthesis of butyrate from carbon dioxide: Production and extraction. Bioelectrochemistry 117, 57–64. https://doi.org/10.1016/j.bioelechem.2017.06.004.

Batlle-Vilanova, P., Rovira-Alsina, L., Puig, S., Balaguer, M.D., Icaran, P., Monsalvo, V. M., Rogalla, F., Colprim, J., 2019. Biogas upgrading, CO$_2$ valorisation and economic revaluation of bioelectrochemical systems through anodic chlorine production in the framework of wastewater treatment plants. Sci. Total Environ. 690, 352–360. https://doi.org/10.1016/j.scitotenv.2019.06.361.

Bekatorou, A., Dima, A., Tsafrakidou, P., Boura, K., Lappa, K., Kandylis, P., Pissaridi, K., Kanellaki, M., Koutinas, A.A., 2016. Downstream extraction process development for recovery of organic acids from a fermentation broth. Bioresour. Technol. 220, 34–37. https://doi.org/10.1016/j.biortech.2016.08.039.

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., Van Mierlo, J., 2017. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. Energies 10, 1314. https://doi.org/10.3390/en10091314.

Bian, B., Bajracharya, S., Xu, J., Pant, D., Saikaly, P.E., 2020. Microbial electrosynthesis from CO$_2$: Challenges, opportunities and perspectives in the context of circular bioeconomy. Bioresour. Technol. 302, 122863. https://doi.org/10.1016/j.biortech.2020.122863.

Blandin, G., Rosselló, B., Monsalvo, V.M., Batlle-Vilanova, P., Viñas, J.M., Rogalla, F., Comas, J., 2019. Volatile fatty acids concentration in real wastewater by forward osmosis. J. Memb. Sci. 575, 60–70. https://doi.org/10.1016/j.memsci.2019.01.006.

Blasco-Gómez, R., Ramió-Pujol, S., Bañeras, L., Colprim, J., Balaguera, M.D., Puig, S., 2019. Unravelling the factors that influence the bio-electrorecycling of carbon dioxide towards biofuels. Green Chem. 21, 684–691. https://doi.org/10.1039/C8GC03417F.

Boyaval, P., Seta, J., Gavach, C., 1993. Concentrated propionic acid production by electrodialysis. Enzyme Microb. Technol. 15, 683–686. https://doi.org/10.1016/0141-0229(93)90069-E.

Bushuyev, O.S., De Luna, P., Dinh, C.T., Tao, L., Saur, G., van de Lagemaat, J., Kelley, S. O., Sargent, E.H., 2018. What should we make with CO$_2$ and how can we make it? Joule 2, 825–832. https://doi.org/10.1016/j.joule.2017.09.003.

Butler, C.S., Lovley, D.R., 2016. How to sustainably feed a microbe: Strategies for biological production of carbon-based commodities with renewable electricity. Front. Microbiol. 7, 1–6. https://doi.org/10.3389/fmicb.2016.01879.

Cerrillo, M., Viñas, M., Bonmatí, A., 2016. Removal of volatile fatty acids and ammonia recovery from unstable anaerobic digesters with a microbial electrolysis cell. Bioresour. Technol. 219, 348–356. https://doi.org/10.1016/j.biortech.2016.07.103.

Chakraborty, I., Das, S., Dubey, B.K., Ghangrekar, M.M., 2020. Novel low cost proton exchange membrane made from sulphonated biochar for application in microbial fuel cells. Mater. Chem. Phys. 239, 122025. https://doi.org/10.1016/j.matchemphys.2019.122025.

Chen, X., Cao, Y., Li, F., Tian, Y., Song, H., 2018. Enzyme-assisted microbial electrosynthesis of poly(3-hydroxybutyrate) via CO$_2$ bioreduction by engineered *Ralstonia eutropha*. ACS Catal. 8, 4429–4437.

Child, M., Kemfert, C., Bogdanov, D., Breyer, C., 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew. Energy 139, 80–101. https://doi.org/10.1016/j.renene.2019.02.077.

Cho, Y.H., Lee, H.D., Park, H.B., 2012. Integrated membrane processes for separation and purification of organic acid from a biomass fermentation process. Ind. Eng. Chem. Res. 51, 10207–10219. https://doi.org/10.1021/ie301023r.

Choudhari, S.K., Cerrone, F., Woods, T., Joyce, K., O'Flaherty, V., O'Connor, K., Babu, R., 2015. Pervaporation separation of butyric acid from aqueous and anaerobic digestion (AD) solutions using PEBA based composite membranes. J. Ind. Eng. Chem. 23, 163–170. https://doi.org/10.1016/j.jiec.2014.08.010.

Christodoulou, X., Okoroafor, T., Parry, S., Velasquez-Orta, S.B., 2017. The use of carbon dioxide in microbial electrosynthesis: Advancements, sustainability and economic feasibility. J. CO$_2$ Util. 18, 390–399. https://doi.org/10.1016/j.jcou.2017.01.027.

Comello, S., Reichelstein, S., 2019. The emergence of cost effective battery storage. Nat. Commun. 10, 1–9. https://doi.org/10.1038/s41467-019-09988-z.

Costa, N.L., Clarke, T.A., Philipp, L.A., Gescher, J., Louro, R.O., Paquete, C.M., 2018. Electron transfer process in microbial electrochemical technologies: The role of cell-surface exposed conductive proteins. Bioresour. Technol. 255, 308–317. https://doi.org/10.1016/j.biortech.2018.01.133.

d'Amore, F., Sunny, N., Iruretagoyena, D., Bezzo, F., Shah, N., 2019. European supply chains for carbon capture, transport and sequestration, with uncertainties in geological storage capacity: Insights from economic optimisation. Comput. Chem. Eng. 129, 106521. https://doi.org/10.1016/j.compchemeng.2019.106521.

De Luna, P., Hahn, C., Higgins, D., Jaffer, S.A., Jaramillo, T.F., Sargent, E.H., 2019. What would it take for renewably powered electrosynthesis to displace petrochemical processes? Science (80-.) 364, 350. https://doi.org/10.1126/science.aav3506.

Dessì, P., Asunis, F., Ravishankar, H., Cocco, F.G., De Gioannis, G., Muntoni, A., Lens, P. N.L., 2020. Fermentative hydrogen production from cheese whey with in-line, concentration gradient-driven butyric acid extraction. Int. J. Hydrogen Energy 45, 24453-24466. doi:doi:10.1016/j.ijhydene.2020.06.081.

Deutzmann, J.S., Spormann, A.M., 2017. Enhanced microbial electrosynthesis by using defined co-cultures. ISME J. 11, 704–714. https://doi.org/10.1038/ismej.2016.149.

Djas, M., Henczka, M., 2018. Reactive extraction of carboxylic acids using organic solvents and supercritical fluids: A review. Sep. Purif. Technol. 201, 106–119. https://doi.org/10.1016/j.seppur.2018.02.010.

Dong, Y., Qu, Y., He, W., Du, Y., Liu, J., Han, X., Feng, Y., 2015. A 90-liter stackable baffled microbial fuel cell for brewery wastewater treatment based on energy self-sufficient mode. Bioresour. Technol. 195, 66–72. https://doi.org/10.1016/j.biortech.2015.06.026.

Dzygiel, P., Wieczorek, P.P., 2010. Supported liquid membranes and their modifications: Definition, classification, theory, stability, application and perspectives, Liquid Membranes 73-140. https://doi.org/10.1016/B978-0-444-53218-3.00003-9.

ElMekawy, A., Hegab, H.M., Mohanakrishna, G., Elbaz, A.F., Bulut, M., Pant, D., 2016. Technological advances in CO$_2$ conversion electro-biorefinery: A step toward commercialization. Bioresour. Technol. 215, 357–370. doi:doi:10.1016/j.biortech.2016.03.023.

European Commission, 2020. Financing the green transition: The European Green Deal investment plan and just transition mechanism. doi:https://ec.europa.eu/commission/presscorner/detail/en/ip_20_17.

European Environment Agency, 2019. The European environment - state and outlook 2020: Knowledge for transition to a sustainable Europe. European Environment. https://doi.org/10.2800/96749.

Farràs, P., Di Giovanni, C., Clifford, J.N., Garrido-Barros, P., Palomares, E., Llobet, A., 2015. Light driven styrene epoxidation and hydrogen generation using H$_2$O as an oxygen source in a photoelectrosynthesis cell. Green Chem. 18, 255–260. https://doi.org/10.1039/c5gc01589h.

Feng, Y., He, W., Liu, J., Wang, X., Qu, Y., Ren, N., 2014. A horizontal plug flow and stackable pilot microbial fuel cell for municipal wastewater treatment. Bioresour. Technol. 156, 132–138. https://doi.org/10.1016/j.biortech.2013.12.104.

Fernández-Naveira, Á., Veiga, M.C., Kennes, C., 2017. H-B-E (hexanol-butanol-ethanol) fermentation for the production of higher alcohols from syngas/waste gas. J. Chem. Technol. Biotechnol. 92, 712–731. https://doi.org/10.1002/jctb.5194.

Fruehauf, H.M., Enzmann, F., Harnisch, F., Ulber, R., Holtmann, D., 2020. Microbial electrosynthesis – An inventory on technology readiness level and performance of different process variants. Biotechnol. J. 15, 2000066. https://doi.org/10.1002/biot.202000066.

Fu, Q., Xiao, S., Li, Z., Li, Y., Kobayashi, H., Li, J., Yang, Y., Liao, Qu., Zhu, X., He, X., Ye, D., Zhang, L., Zhong, M., 2018. Hybrid solar-to-methane conversion system with a Faradaic efficiency of up to 96%. Nano Energy 53, 232–239.

Future Market Insights, 2020. Global caproic acid market share. Industry analysis report 2017-2027 [WWW Document]. URL. https://www.futuremarketinsights.com/reports/caproic-acid-market.

Ganigué, R., Puig, S., Batlle-Vilanova, P., Balaguer, M.D., Colprim, J., 2015. Microbial electrosynthesis of butyrate from carbon dioxide. Chem. Commun. 51, 3235–3238. https://doi.org/10.1039/c4cc10121a.

Gavilanes, J., Reddy, C.N., Min, B., 2019. Microbial electrosynthesis of bioalcohols through reduction of high concentrations of volatile fatty acids. Energy & Fuels 33, 4264–4271. https://doi.org/10.1021/acs.energyfuels.8b04215.

Geppert, F., Liu, D., Weidner, E., ter Heijne, A., 2019. Redox-flow battery design for a methane-producing bioelectrochemical system. Int. J. Hydrogen Energy 44, 21464–21469. https://doi.org/10.1016/j.ijhydene.2019.06.189.

Giang, H., Zhang, J., Zhu, Z., Suni, I.I., Liang, Y., 2018. Single-chamber microbial electrochemical cell for CH_4 production from CO_2 utilizing a microbial consortium. Int. J. Energy Res. 42, 1308–1315. https://doi.org/10.1002/er.3931.

Giddings, C.G.S., Nevin, K.P., Woodward, T., Lovley, D.R., Butler, C.S., 2015. Simplifying microbial electrosynthesis reactor design. Front. Microbiol. 6, 1–6. https://doi.org/10.3389/fmicb.2015.00468.

Gil-Carrera, L., Escapa, A., Mehta, P., Santoyo, G., Guiot, S.R., Morán, A., Tartakovsky, B., 2013. Microbial electrolysis cell scale-up for combined wastewater treatment and hydrogen production. Bioresour. Technol. 130, 584–591. https://doi.org/10.1016/j.biortech.2012.12.062.

Gildemyn, S., Verbeeck, K., Slabbinck, R., Andersen, S.J., Prévoteau, A., Rabaey, K., 2015. Integrated production, extraction, and concentration of acetic acid from CO_2 through microbial electrosynthesis. Environ. Sci. Technol. Lett. 2, 325–328. https://doi.org/10.1021/acs.estlett.5b00212.

Global Market Insights, 2020. Butyric acid market by application, type & geography [WWW Document]. URL. https://www.gminsights.com/industry-analysis/butyric-acid-market.

Gong, Y., Ebrahim, A., Feist, A.M., Embree, M., Zhang, T., Lovley, D., Zengler, K., 2013. Sulfide-driven microbial electrosynthesis. Environ. Sci. Technol. 47, 568–573. https://doi.org/10.1021/es303837j.

Greenman, J., Ieropoulos, I.A., 2017. Allometric scaling of microbial fuel cells and stacks: The lifeform case for scale-up. J. Power Sources 356, 365–370. https://doi.org/10.1016/j.jpowsour.2017.04.033.

Grim, R.G., Huang, Z., Guarnieri, M.T., Ferrell III, J.R., Tao, L., Schaidle, J.A., 2020. Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO_2 utilization. Energy Environ. Sci. 13, 472–494. https://doi.org/10.1039/c9ee02410g.

Gurung, A., Oh, S.E., 2012. The performance of serially and parallelly connected microbial fuel cells. Energy Sources, Part A Recover. Util. Environ. Eff. 34, 1591–1598. https://doi.org/10.1080/15567036.2011.629277.

Haas, T., Krause, R., Weber, R., Demler, M., Schmid, G., 2018. Technical photosynthesis involving CO_2 electrolysis and fermentation. Nat. Catal. 1, 32–39. https://doi.org/10.1038/s41929-017-0005-1.

Hatzell, M.C., Kim, Y., Logan, B.E., 2013. Powering microbial electrolysis cells by capacitor circuits charged using microbial fuel cell. J. Power Sources 229, 198–202. https://doi.org/10.1016/j.jpowsour.2012.12.006.

Henczka, M., Djas, M., 2016. Reactive extraction of acetic acid and propionic acid using supercritical carbon dioxide. J. Supercrit. Fluids 110, 154–160. https://doi.org/10.1016/j.supflu.2015.11.018.

Hiegemann, H., Littfinski, T., Krimmler, S., Lübken, M., Klein, D., Schmelz, K.G., Ooms, K., Pant, D., Wichern, M., 2019. Performance and inorganic fouling of a submergible 255 L prototype microbial fuel cell module during continuous long-term operation with real municipal wastewater under practical conditions. Bioresour. Technol. 294, 122227. https://doi.org/10.1016/j.biortech.2019.122227.

Huang, C., Xu, T., Zhang, Y., Xue, Y., Chen, G., 2007. Application of electrodialysis to the production of organic acids: State-of-the-art and recent developments. J. Memb. Sci. 288, 1–12. https://doi.org/10.1016/j.memsci.2006.11.026.

Jafary, T., Rahimnejad, M., Ghoreyshi, A.A., Najafpour, G., Hghparast, F., Daud, W.R.W., 2013. Assessment of bioelectricity production in microbial fuel cells through series and parallel connections. Energy Convers. Manag. 75, 256–262. https://doi.org/10.1016/j.enconman.2013.06.032.

Jiang, Y., Jianxiong Zeng, R., 2018. Expanding the product spectrum of value added chemicals in microbial electrosynthesis through integrated process design—A review. Bioresour. Technol. 269, 503–512. https://doi.org/10.1016/j.biortech.2018.08.101.

Jiang, Y., Su, M., Zhang, Y., Zhan, G., Tao, Y., Li, D., 2013. Bioelectrochemical systems for simultaneously production of methane and acetate from carbon dioxide at relatively high rate. Int. J. Hydrogen Energy 38, 3497–3502. https://doi.org/10.1016/j.ijhydene.2012.12.107.

Jiang, Y., May, H.D., Lu, L., Liang, P., Huang, X., Ren, Z.J., 2019. Carbon dioxide and organic waste valorization by microbial electrosynthesis and electro-fermentation. Water Res. 149, 42–55. https://doi.org/10.1016/j.watres.2018.10.092.

Jiang, Y., Chu, N., Qian, D.K., Jianxiong Zeng, R., 2020. Microbial electrochemical stimulation of caproate production from ethanol and carbon dioxide. Bioresour. Technol. 295, 122266. https://doi.org/10.1016/j.biortech.2019.122266.

Jones, R.J., Massanet-Nicolau, J., Guwy, A., Premier, G.C., Dinsdale, R.M., Reilly, M., 2015. Removal and recovery of inhibitory volatile fatty acids from mixed acid fermentations by conventional electrodialysis. Bioresour. Technol. 189, 279–284. https://doi.org/10.1016/j.biortech.2015.04.001.

Jones, R.J., Massanet-Nicolau, J., Mulder, M.J.J., Premier, G., Dinsdale, R., Guwy, A., 2017. Increased biohydrogen yields, volatile fatty acid production and substrate utilisation rates via the electrodialysis of a continually fed sucrose fermenter. Bioresour. Technol. 229, 46–52. https://doi.org/10.1016/j.biortech.2017.01.015.

Jourdin, L., Grieger, T., Monetti, J., Flexer, V., Freguia, S., Lu, Y., Chen, J., Romano, M., Wallace, G.G., Keller, J., 2015. High acetic acid production rate obtained by microbial electrosynthesis from carbon dioxide. Environ. Sci. Technol. 49, 13566–13574. https://doi.org/10.1021/acs.est.5b03821.

Jourdin, L., Freguia, S., Flexer, V., Keller, J., 2016. Bringing high-rate, CO_2-based microbial electrosynthesis closer to practical implementation through improved electrode design and operating conditions. Environ. Sci. Technol. 50, 1982–1989. https://doi.org/10.1021/acs.est.5b04431.

Jourdin, L., Raes, S.M.T., Buisman, C.J.N., Strik, D.P.B.T.B., 2018. Critical biofilm growth throughout unmodified carbon felts allows continuous bioelectrochemical chain elongation from CO_2 up to caproate at high current density. Front. Energy Res. 6, 7. https://doi.org/10.3389/fenrg.2018.00007.

Jourdin, L., Winkelhorst, M., Rawls, B., Buisman, C.J.N., Strik, D.P.B.T.B., 2019. Enhanced selectivity to butyrate and caproate above acetate in continuous bioelectrochemical chain elongation from CO_2: Steering with CO_2 loading rate and hydraulic retention time. Bioresour. Technol. Reports 7, 100284. https://doi.org/10.1016/j.biteb.2019.100284.

Jourdin, L., Sousa, J., van Stralen, N., Strik, D.P.B.T.B., 2020. Techno-economic assessment of microbial electrosynthesis from CO_2 and/or organics: An interdisciplinary roadmap towards future research and application. Appl. Energy 279, 115775. https://doi.org/10.1016/j.apenergy.2020.115775.

Karthikeyan, R., Singh, R., Bose, A., 2019. Microbial electron uptake in microbial electrosynthesis: A mini-review. J. Ind. Microbiol. Biotechnol. 46, 1419–1426. https://doi.org/10.1007/s10295-019-02166-6.

Katuri, K.P., Kalathil, S., Ragab, A., Bian, B., Alqahtani, M.F., Pant, D., Saikaly, P.E., 2018. Dual-function electrocatalytic and macroporous hollow-fiber cathode for converting waste streams to valuable resources using microbial electrochemical systems. Adv. Mater. 30, 1707072. https://doi.org/10.1002/adma.201707072.

Khalili, H.B., Mohebbi-Kalhori, D., Afarani, M.S., 2017. Microbial fuel cell (MFC) using commercially available unglazed ceramic wares: Low-cost ceramic separators suitable for scale-up. Int. J. Hydrogen Energy 42, 8233–8241. https://doi.org/10.1016/j.ijhydene.2017.02.095.

Kim, Y., Hatzell, M.C., Hutchinson, A.J., Logan, B.E., 2011. Capturing power at higher voltages from arrays of microbial fuel cells without voltage reversal. Energy Environ. Sci. 4, 4662–4667. https://doi.org/10.1039/c1ee02451e.

Kirner, J.T., Finke, R.G., 2017. Water-oxidation photoanodes using organic light-harvesting materials: A review. J. Mater. Chem. A 5, 19560–19592. https://doi.org/10.1039/c7ta05709a.

Kracke, F., Lai, B., Yu, S., Krömer, J.O., 2018. Balancing cellular redox metabolism in microbial electrosynthesis and electro fermentation – A chance for metabolic engineering. Metab. Eng. 45, 109–120. https://doi.org/10.1016/j.ymben.2017.12.003.

Kracke, F., Wong, A.B., Maegaard, K., Deutzmann, J.S., Hubert, M.A., Hahn, C., Jaramillo, T.F., Spormann, A.M., 2019. Robust and biocompatible catalysts for efficient hydrogen-driven microbial electrosynthesis. Commun. Chem. 2, 45. https://doi.org/10.1038/s42004-019-0145-0.

Kracke, F., Deutzmann, J.S., Gu, W., Spormann, A.M., 2020. *In situ* electrochemical H_2 production for efficient and stable power-to-gas electromethanogenesis. Green Chem. 22, 6194–6203. https://doi.org/10.1039/d0gc01894e.

LaBelle, E.V., May, H.D., 2017. Energy efficiency and productivity enhancement of microbial electrosynthesis of acetate. Front. Microbiol. 8, 756. https://doi.org/10.3389/fmicb.2017.00756.

Lee, S.Y., Lim, S.Y., Seo, D., Lee, J.Y., Chung, T.D., 2016. Light-driven highly selective conversion of CO_2 to formate by electrosynthesized enzyme/cofactor thin film electrode. Adv. Energy Mater. 6, 1502207. https://doi.org/10.1002/aenm.201502207.

Lee, S.Y., Kim, H.U., Chae, T.U., Cho, J.S., Kim, J.W., Shin, J.H., Kim, D.I., Ko, Y.S., Jang, W.D., Jang, Y.S., 2019. A comprehensive metabolic map for production of bio-based chemicals. Nat. Catal. 2, 18–33. https://doi.org/10.1038/s41929-018-0212-4.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., Fennell, P.S., 2017. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. Int. J. Greenh. Gas Control 61, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020.

Liang, P., Duan, R., Jiang, Y., Zhang, X., Qiu, Y., Huang, X., 2018. One-year operation of 1000-L modularized microbial fuel cell for municipal wastewater treatment. Water Res. 141, 1–8. https://doi.org/10.1016/J.WATRES.2018.04.066.

Liu, C., Gallagher, J.J., Sakimoto, K.K., Nichols, E.M., Chang, C.J., Chang, M.C.Y., Yang, P., 2015. Nanowire-bacteria hybrids for unassisted solar carbon dioxide fixation to value-added chemicals. Nano Lett. 15, 3634–3639. https://doi.org/10.1021/acs.nanolett.5b01254.

Liu, X., Wu, J., Gong, B., 2016. Series and parallel connection of anaerobic fluidized bed microbial fuel cells (MFCs). Int. J. Appl. Microbiol. Biotechnol. Res. 4, 7–14.

Logan, B.E., Rossi, R., Ragab, A., Saikaly, P.E., 2019. Electroactive microorganisms in bioelectrochemical systems. Nat. Rev. Microbiol. 17, 307–319. https://doi.org/10.1038/s41579-019-0173-x.

Lopez, A.M., Hestekin, J.A., 2015. Improved organic acid purification through wafer enhanced electrodeionization utilizing ionic liquids. J. Memb. Sci. 493, 200–205. https://doi.org/10.1016/j.memsci.2015.06.008.

López-Garzón, C.S., Straathof, A.J.J., 2014. Recovery of carboxylic acids produced by fermentation. Biotechnol. Adv. 32, 873–904. https://doi.org/10.1016/j.biotechadv.2014.04.002.

Luckow, P., Stanton, E.A., Fields, S., Ong, W., Biewald, B., Jackson, S., Fisher, J., 2016. Spring 2016 National carbon dioxide price forecast, Synapse Energy Economics. doi: 617.661.3248.

Marshall, C.W., Ross, D.E., Fichot, E.B., Norman, R.S., May, H.D., 2013. Long-term operation of microbial electrosynthesis systems improves acetate production by autotrophic microbiomes. Environ. Sci. Technol. 47, 6023–6029. https://doi.org/10.1021/es400341b.

Marshall, C.W., Ross, D.E., Handley, K.M., Weisenhorn, P.B., Edirisinghe, J.N., Henry, C. S., Gilbert, J.A., May, H.D., Norman, R.S., 2017. Metabolic reconstruction and modeling microbial electrosynthesis. Sci. Rep. 7, 8391. https://doi.org/10.1038/s41598-017-08877-z.

Masnadi, B.M.S., El-Houjeiri, H.M., Schunack, D., Li, Y., Englander, G., Badahdah, A., Monfort, J., Anderson, J.E., Wallington, T.J., Bergerson, J.A., Gordon, D., Koomey, J., Azevedo, I.L., Bi, X.T., Duffy, J.E., Heath, G.A., Keoleian, A., Mcglade, C., Meehan, D.N., Yeh, S., You, F., Brandt, A.R., 2018. Global carbon intensity of crude oil production. Science (80-.). 361, 851–853.

Mateos, R., Sotres, A., Alonso, R.M., Morán, A., Escapa, A., 2019. Enhanced CO$_2$ conversion to acetate through microbial electrosynthesis (MES) by continuous headspace gas recirculation. Energies 12, 3297.

Mateos, R., Escapa, A., San-Martín, M.I., De Wever, H., Sotres, A., Pant, D., 2020. Long-term open circuit microbial electrosynthesis system promotes methanogenesis. J. Energy Chem. 41, 3–6. https://doi.org/10.1016/j.jechem.2019.04.020.

Mayyas, A., Ruth, M., Pivovar, B., Bender, G., Wipke, K., Mayyas, A., Ruth, M., Pivovar, B., Bender, G., Wipke, K., 2019. Manufacturing cost analysis for proton exchange membrane water electrolyzers [WWW Document]. URL. https://www.nrel.gov/docs/fy19osti/72740.pdf.

Mohanakrishna, G., Abu Reesh, I.M., Vanbroekhoven, K., Pant, D., 2020. Microbial electrosynthesis feasibility evaluation at high bicarbonate concentrations with enriched homoacetogenic biocathode. Sci. Total Environ. 715, 137003. https://doi.org/10.1016/j.scitotenv.2020.137003.

Moon, P.J., Parulekar, S.J., Tsai, S.P., 1998. Competitive anion transport in desalting of mixtures of organic acids by batch electrodialysis. J. Memb. Sci. 141, 75–89. https://doi.org/10.1016/S0376-7388(97)00292-5.

Nevin, K.P., Woodard, T.L., Franks, A.E., Summers, Z.M., Lovley, D.R., 2010. Microbial electrosynthesis: Feeding microbes electricity to convert carbon dioxide and water to multicarbon extracellular organic compounds. MBio 1, e00103–e00110. https://doi.org/10.1128/mBio.00103-10.Editor.

Nevin, K.P., Hensley, S.A., Franks, A.E., Summers, Z.M., Ou, J., Woodard, T.L., Snoeyenbos-West, O.L., Lovley, D.R., 2011. Electrosynthesis of organic compounds from carbon dioxide is catalyzed by a diversity of acetogenic microorganisms. Appl. Environ. Microbiol. 77, 2882–2886. https://doi.org/10.1128/AEM.02642-10.

Nuchnoi, P., Yano, T., Nishio, N., Nagai, S., 1987. Extraction of volatile fatty acids from diluted aqueous solution using a supported liquid membrane. J. Ferment. Technol. 65, 301–310. https://doi.org/10.1016/0385-6380(87)90092-6.

Osset-Álvarez, M., Rovira-Alsina, L., Pous, N., Blasco-Gómez, R., Colprim, J., Balaguer, M.D., Puig, S., 2019. Niches for bioelectrochemical systems on the recovery of water, carbon and nitrogen in wastewater treatment plants. Biomass and Bioenergy 130, 105380. https://doi.org/10.1016/j.biombioe.2019.105380.

Outram, V., Zhang, Y., 2018. Solvent-free membrane extraction of volatile fatty acids from acidogenic fermentation. Bioresour. Technol. 270, 400–408. https://doi.org/10.1016/j.biortech.2018.09.057.

Pabby, A.K., Sastre, A.M., 2013. State-of-the-art review on hollow fibre contactor technology and membrane-based extraction processes. J. Memb. Sci. 430, 263–303. https://doi.org/10.1016/j.memsci.2012.11.060.

Patil, S.A., Arends, J.B.A., Vanwonterghem, I., Van Meerbergen, J., Guo, K., Tyson, G.W., Rabaey, K., 2015. Selective enrichment establishes a stable performing community for microbial electrosynthesis of acetate from CO$_2$. Environ. Sci. Technol. 49, 8833–8843. https://doi.org/10.1021/es506149d.

Pepè Sciarria, T., Batlle-Vilanova, P., Colombo, B., Scaglia, B., Balaguer, M.D., Colprim, J., Puig, S., Adani, F., 2018. Bio-electrorecycling of carbon dioxide into bioplastics. Green Chem. 20, 4058–4066. https://doi.org/10.1039/c8gc01771a.

Philips, J., 2020. Extracellular electron uptake by acetogenic bacteria: Does H$_2$ consumption favor the H$_2$ evolution reaction on a cathode or metallic iron? Front. Microbiol. 10, 2997. https://doi.org/10.3389/fmicb.2019.02997.

Pihu, T., Konist, A., Neshumayev, D., Loo, L., Molodtsov, A., Valtsev, A., 2017. Full-scale tests on the co-firing of peat and oil shale in an oil shale fired circulating fluidized bed boiler. Oil Shale 34, 250–262. https://doi.org/10.3176/oil.2017.3.04.

Plácido, J., Zhang, Y., 2018. Evaluation of esterification and membrane based solvent extraction as methods for the recovery of short chain volatile fatty acids from slaughterhouse blood anaerobic mixed fermentation. Waste and Biomass Valorization 9, 1767–1777. https://doi.org/10.1007/s12649-017-9952-7.

Prévoteau, A., Carvajal-Arroyo, J.M., Ganigué, R., Rabaey, K., 2020. Microbial electrosynthesis from CO$_2$: Forever a promise? Curr. Opin. Biotechnol. 62, 48–57. https://doi.org/10.1016/j.copbio.2019.08.014.

Qin, Y., Sheth, J.P., Sirkar, K.K., 2003. Pervaporation membranes that are highly selective for acetic acid over water. Ind. Eng. Chem. Res. 42, 582–595. https://doi.org/10.1021/ie020414w.

Rabaey, K., Rozendal, R.A., 2010. Microbial electrosynthesis — revisiting the electrical route for microbial production. Nat. Rev. Microbiol. 8, 706.

Raes, S.M.T., Jourdin, L., Buisman, C.J.N., Strik, D.P.B.T.B., 2017. Continuous long-term bioelectrochemical chain elongation to butyrate. ChemElectroChem 4, 386–395. https://doi.org/10.1002/celc.201600587.

Rebecchi, S., Pinelli, D., Bertin, L., Zama, F., Fava, F., Frascari, D., 2016. Volatile fatty acids recovery from the effluent of an acidogenic digestion process fed with grape pomace by adsorption on ion exchange resins. Chem. Eng. J. 306, 629–639. https://doi.org/10.1016/j.cej.2016.07.101.

Reyhanitash, E., Zaalberg, B., Kersten, S.R.A., Schuur, B., 2016. Extraction of volatile fatty acids from fermented wastewater. Sep. Purif. Technol. 161, 61–68. https://doi.org/10.1016/j.seppur.2016.01.037.

Reyhanitash, E., Kersten, S.R.A., Schuur, B., 2017. Recovery of volatile fatty acids from fermented wastewater by adsorption. ACS Sustain. Chem. Eng. 5, 9176–9184. https://doi.org/10.1021/acssuschemeng.7b02095.

Rossi, R., Jones, D., Myung, J., Zikmund, E., Yang, W., Alvarez, Y., Pant, D., Evans, P.J., Page, M.A., Cropek, D.M., Logan, B.E., 2019. Evaluating a multi-panel air cathode through electrochemical and biotic tests. Water Res. 148, 51–59. https://doi.org/10.1016/j.watres.2018.10.022.

Rosso, D., Stenstrom, M.K., 2008. The carbon-sequestration potential of municipal wastewater treatment. Chemosphere 70, 1468–1475. https://doi.org/10.1016/j.chemosphere.2007.08.057.

Rovira-Alsina, L., Perona-Vico, E., Bañeras, L., Colprim, J., Balaguer, M.D., Puig, S., 2020. Thermophilic bio-electro CO$_2$ recycling into organic compounds. Green Chem. 22, 2947–2955. https://doi.org/10.1039/x0xx00000x.

Roy, M., Yadav, R., Chiranjeevi, P., Patil, S.A., 2021. Direct utilization of industrial carbon dioxide with low impurities for acetate production via microbial electrosynthesis. Bioresour. Technol. 320, 124289 https://doi.org/10.1016/j.biortech.2020.124289.

Russell, T.P., 2013. Improved cathode for high efficient microbial-catalyzed reduction in microbial electrosynthesis cells 14290–14294. doi:https://doi.org/10.1039/c3cp52697f.

Saboe, P.O., Manker, L.P., Michener, W.E., Peterson, D.J., Brandner, D.G., Deutch, S.P., Kumar, M., Cywar, R.M., Beckham, G.T., Karp, E.M., 2018. In situ recovery of bio-based carboxylic acids. Green Chem. 20, 1791–1804. https://doi.org/10.1039/c7gc03747c.

Sadhukhan, J., Lloyd, J.R., Scott, K., Premier, G.C., Yu, E.H., Curtis, T., Head, I.M., 2016. A critical review of integration analysis of microbial electrosynthesis (MES) systems with waste biorefineries for the production of biofuel and chemical from reuse of CO$_2$. Renew. Sustain. Energy Rev. 56, 116–132. https://doi.org/10.1016/j.rser.2015.11.015.

Saito, T., Yoshino, Y., Kawanabe, H., Sasaki, M., Goto, M., 2009. Adsorptive removal of organic acids and furans from hydrothermal treatment process of biomass. Sep. Sci. Technol. 44, 2761–2773. https://doi.org/10.1080/01496390903014409.

Salar-García, M.J., Ortiz-Martínez, V.M., Baicha, Z., de los Ríos, A.P., Hernández-Fernández, F.J., 2016. Scaled-up continuous up-flow microbial fuel cell based on novel embedded ionic liquid-type membrane-cathode assembly. Energy 101, 113–120. https://doi.org/10.1016/j.energy.2016.01.078.

Sánchez, O.G., Birdja, Y.Y., Bulut, M., Vaes, J., Breugelmans, T., Pant, D., 2019. Recent advances in industrial CO$_2$ electroreduction. Curr. Opin. Green Sustain. Chem. 16, 47–56. https://doi.org/10.1016/j.cogsc.2019.01.005.

Sánchez, C., Dessì, P., Duffy, M., Lens, P.N.L., 2020. Microbial electrochemical technologies: Electronic circuitry and characterization tools. Biosens. Bioelectron. 150, 111884 https://doi.org/10.1016/j.bios.2019.111884.

Scoma, A., Varela-Corredor, F., Bertin, L., Gostoli, C., Bandini, S., 2016. Recovery of VFAs from anaerobic digestion of dephenolized olive mill wastewaters by electrodialysis. Sep. Purif. Technol. 159, 81–91. https://doi.org/10.1016/j.seppur.2015.12.029.

Shi, L., Hu, Y., Xie, S., Wu, G., Hu, Z., Zhan, X., 2018. Recovery of nutrients and volatile fatty acids from pig manure hydrolysate using two-stage bipolar membrane electrodialysis. Chem. Eng. J. 334, 134–142. https://doi.org/10.1016/j.cej.2017.10.010.

Shin, H.J., Jung, K.A., Nam, C.W., Park, J.M., 2017. A genetic approach for microbial electrosynthesis system as biocommodities production platform. Bioresour. Technol. 245, 1421–1429. https://doi.org/10.1016/j.biortech.2017.05.077.

Song, T. shun, Zhang, H., Liu, H., Zhang, D., Wang, H., Yang, Y., Yuan, H., Xie, J., 2017. High efficiency microbial electrosynthesis of acetate from carbon dioxide by a self-assembled electroactive biofilm. Bioresour. Technol. 243, 573–582. https://doi.org/10.1016/j.biortech.2017.06.164.

Sonibare, J.A., Akeredolu, F.A., 2004. A theoretical prediction of non-methane gaseous emissions from natural gas combustion. Energy Policy 32, 1653–1665. https://doi.org/10.1016/j.enpol.2004.02.008.

Srikanth, S., Kumar, M., Singh, D., Singh, M.P., Puri, S.K., Ramakumar, S.S.V., 2018a. Long-term operation of electro-biocatalytic reactor for carbon dioxide transformation into organic molecules. Bioresour. Technol. 265, 66–74. https://doi.org/10.1016/j.biortech.2017.12.075.

Srikanth, S., Singh, D., Vanbroekhoven, K., Pant, D., Kumar, M., Puri, S.K., Ramakumar, S.S.V., 2018b. Electro-biocatalytic conversion of carbon dioxide to alcohols using gas diffusion electrode. Bioresour. Technol. 265, 45–51. https://doi.org/10.1016/j.biortech.2018.02.058.

Stang, C., Harnisch, F., 2016. The dilemma of supporting electrolytes for electroorganic synthesis: A case study on Kolbe electrolysis. ChemSusChem 9, 50–60. https://doi.org/10.1002/cssc.201501407.

Stroe, D.I., Zaharof, A., Iov, F., 2018. Power and energy management with battery storage for a hybrid residential PV-wind system - A case study for Denmark, in: Energy Procedia. Elsevier Ltd, pp. 464–477. doi:https://doi.org/10.1016/j.egypro.2018.11.033.

Sun, Y., Zwolińska, E., Chmielewski, A.G., 2016. Abatement technologies for high concentrations of NO$_X$ and SO$_2$ removal from exhaust gases: A review. Crit. Rev. Environ. Sci. Technol. 46, 119–142. https://doi.org/10.1080/10643389.2015.1063334.

Tahir, K., Miran, W., Jang, J., Shahzad, A., Moztahida, M., Kim, B., Lee, D.S., 2020. A novel MXene-coated biocathode for enhanced microbial electrosynthesis performance. Chem. Eng. J. 381, 122687 https://doi.org/10.1016/j.cej.2019.122687.

Tashiro, Y., Hirano, S., Matson, M.M., Atsumi, S., Kondo, A., 2018. Electrical-biological hybrid system for CO$_2$ reduction. Metab. Eng. 47, 211–218. https://doi.org/10.1016/j.ymben.2018.03.015.

Thung, W.E., Ong, S.A., Ho, L.N., Wong, Y.S., Ridwan, F., Oon, Y.L., Oon, Y.S., Lehl, H.K., 2019. Enhancement of mass and charge transport in scaled-up microbial fuel cell by using innovative configuration of bioanode. Int. J. Environ. Sci. Technol. 16, 8175–8184. https://doi.org/10.1007/s13762-019-02390-8.

Torella, J.P., Gagliardi, C.J., Chen, J.S., Bediako, D.K., Colón, B., Way, J.C., Silver, P.A., Nocera, D.G., 2015. Efficient solar-to-fuels production from a hybrid microbial-water-splitting catalyst system. Proc. Natl. Acad. Sci. U. S. A. 112, 2337–2342. https://doi.org/10.1073/pnas.1424872112.

Tremblay, P.L., Angenent, L.T., Zhang, T., 2017. Extracellular electron uptake: Among autotrophs and mediated by surfaces. Trends Biotechnol. 35, 360–371. https://doi.org/10.1016/j.tibtech.2016.10.004.

United Nations, 2015. Paris Agreement [WWW Document]. URL. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

Ursúa, A., Gandía, L.M., Sanchis, P., 2012. Hydrogen production from water electrolysis: Current status and future trends. Proc. IEEE 100, 410–426. https://doi.org/10.1109/JPROC.2011.2156750.

Vassilev, I., Hernandez, P.A., Batlle-Vilanova, P., Freguia, S., Krömer, J.O., Keller, J., Ledezma, P., Virdis, B., 2018. Microbial electrosynthesis of isobutyric, butyric, caproic acids, and corresponding alcohols from carbon dioxide. ACS Sustain. Chem. Eng. 6, 8485–8493. https://doi.org/10.1021/acssuschemeng.8b00739.

Vassilev, I., Kracke, F., Freguia, S., Keller, J., Krömer, J.O., Ledezma, P., Virdis, B., 2019. Microbial electrosynthesis system with dual biocathode arrangement for simultaneous acetogenesis, solventogenesis and carbon chain elongation. Chem. Commun. 55, 4351–4354. https://doi.org/10.1039/c9cc00208a.

Vilajeliu-Pons, A., Puig, S., Salcedo-Dávila, I., Balaguer, M.D., Colprim, J., 2017. Long-term assessment of six-stacked scaled-up MFCs treating swine manure with different electrode materials. Environ. Sci. Water Res. Technol. 3, 947–959. https://doi.org/10.1039/c7ew00079k.

Voeikova, T.A., Zhuravliova, O.A., Debabov, V.G., 2020. Comparative analysis of legal regulation of industrial use of genetic-engineering-modified microoranisms in the United States, the European Union and Russian Federation. Mol. Genet. Microbiol. Virol. 35, 69–77. https://doi.org/10.17116/molgen20203802167.

Walter, X.A., Santoro, C., Greenman, J., Ieropoulos, I.A., 2020. Scalability and stacking of self-stratifying microbial fuel cells treating urine. Bioelectrochemistry 133, 107491. https://doi.org/10.1016/j.bioelechem.2020.107491.

Weekes, D.M., Salvatore, D.A., Reyes, A., Huang, A., Berlinguette, C.P., 2018. Electrolytic CO_2 reduction in a flow cell. Acc. Chem. Res. 51, 910–918. https://doi.org/10.1021/acs.accounts.8b00010.

Wilberforce, T., Baroutaji, A., Soudan, B., Al-Alami, A.H., Olabi, A.G., 2019. Outlook of carbon capture technology and challenges. Sci. Total Environ. 657, 56–72. https://doi.org/10.1016/j.scitotenv.2018.11.424.

Xiang, Y., Liu, G., Zhang, R., Lu, Y., Luo, H., 2017. High-efficient acetate production from carbon dioxide using a bioanode microbial electrosynthesis system with bipolar membrane. Bioresour. Technol. 233, 227–235. https://doi.org/10.1016/j.biortech.2017.02.104.

Xiao, S., Li, Z., Fu, Q., Li, Y., Li, J., Zhang, L., Liao, Q., Zhu, X., 2020. Hybrid microbial photoelectrochemical system reduces CO_2 to CH_4 with 1.28% solar energy conversion efficiency. Chem. Eng. J. 390, 124530 https://doi.org/10.1016/j.cej.2020.124530.

Xiong, B., Richard, T.L., Kumar, M., 2015. Integrated acidogenic digestion and carboxylic acid separation by nanofiltration membranes for the lignocellulosic carboxylate platform. J. Memb. Sci. 489, 275–283. https://doi.org/10.1016/j.memsci.2015.04.022.

Xu, J., Guzman, J.J.L., Andersen, S.J., Rabaey, K., Angenent, L.T., 2015. In-line and selective phase separation of medium-chain carboxylic acids using membrane electrolysis. Chem. Commun. 51, 6847–6850. https://doi.org/10.1039/C5CC01897H.

Xue, S., Wu, C., Wu, Y., Zhang, C., 2017. An optimized process for treating sodium acetate waste residue: Coupling of diffusion dialysis or electrodialysis with bipolar membrane electrodialysis. Chem. Eng. Res. Des. 129, 237–247. https://doi.org/10.1016/j.cherd.2017.11.013.

Yan, Y., Gao, Y., Zheng, H., Yuan, B., Zhang, Q., Gu, Y., Zhuang, G., Wei, Z., Yao, Z., Zhong, X., Li, X., Wang, J., 2020. Simultaneous electrochemical ozone production and hydrogen evolution by using tantalum-based nanorods electrocatalysts. Appl. Catal. B Environ. 266, 118632 https://doi.org/10.1016/j.apcatb.2020.118632.

Yesil, H., Tugtas, A.E., Bayrakdar, A., Calli, B., 2014. Anaerobic fermentation of organic solid wastes: Volatile fatty acid production and separation. Water Sci. Technol. 69, 2132–2138. https://doi.org/10.2166/wst.2014.132.

Yin, Z., Peng, H., Wei, X., Zhou, H., Gong, J., Huai, M., Xiao, L., Wang, G., Lu, J., Zhuang, L., 2019. An alkaline polymer electrolyte CO_2 electrolyzer operated with pure water. Energy Environ. Sci. 12, 2455–2462. https://doi.org/10.1039/c9ee01204d.

Zacharof, M.P., Mandale, S.J., Williams, P.M., Lovitt, R.W., 2016. Nanofiltration of treated digested agricultural wastewater for recovery of carboxylic acids. J. Clean. Prod. 112, 4749–4761. https://doi.org/10.1016/j.jclepro.2015.07.004.

Zamora, P., Georgieva, T., Ter Heijne, A., Sleutels, T.H.J.A., Jeremiasse, A.W., Saakes, M., Buisman, C.J.N., Kuntke, P., 2017. Ammonia recovery from urine in a scaled-up Microbial Electrolysis Cell. J. Power Sources 356, 491–499. https://doi.org/10.1016/j.jpowsour.2017.02.089.

Zhang, Y., Angelidaki, I., 2015. Bioelectrochemical recovery of waste-derived volatile fatty acids and production of hydrogen and alkali. Water Res. 81, 188–195. https://doi.org/10.1016/j.watres.2015.05.058.

Zhang, T., Tremblay, P.-L., 2019. Possible industrial applications for microbial electrosynthesis from carbon dioxide. In: Biomass, Biofuels and Biochemicals, Microbial Electrochemical Technology: Sustainable Platform for Fuels, Chemicals. Remediation 825–842. https://doi.org/10.1016/B978-0-444-64052-9.00034-0.

Zhang, X., Li, C., Wang, Y., Luo, J., Xu, T., 2011. Recovery of acetic acid from simulated acetaldehyde wastewaters: Bipolar membrane electrodialysis processes and membrane selection. J. Memb. Sci. 379, 184–190. https://doi.org/10.1016/j.memsci.2011.05.059.

Zhang, T., Nie, H., Bain, T.S., Lu, H., Cui, M., Snoeyenbos-West, O.L., Franks, A.E., Nevin, K.P., Russell, T.P., Lovley, D.R., 2013. Improved cathode materials for microbial electrosynthesis. Energy Environ. Sci. 6, 217–224. https://doi.org/10.1039/c2ee23350a.

Zhao, H.-Z., Zhang, Y., Chang, Y.-Y., Li, Z.-S., 2012. Conversion of a substrate carbon source to formic acid for carbon dioxide emission reduction utilizing series-stacked microbial fuel cells. J. Power Sources 217, 59–64. https://doi.org/10.1016/j.jpowsour.2012.06.014.

Zhuang, L., Zheng, Y., Zhou, S., Yuan, Y., Yuan, H., Chen, Y., 2012. Scalable microbial fuel cell (MFC) stack for continuous real wastewater treatment. Bioresour. Technol. 106, 82–88. https://doi.org/10.1016/j.biortech.2011.11.019.